FACULTAD DE INGENIERÍA Y ARQUITECTURA

ESCUELA PROFESIONAL DE INGENIERÍA CIVIL

Diseño de concreto permeable con plastificante para mejorar la resistencia a la compresión como alternativa para el drenaje pluvial en Juliaca 2021

TESIS PARA OBTENER EL TÍTULO PROFESIONAL DE:

INGENIERO CIVIL

AUTORES:

Cusi Cusi, Edwin (ORCID: 0000-0002-9719-2082)

Ticona Ali, Alex Hermenegildo (ORCID: 0000-0003-4301-0893)

ASESOR:

Mg. Rodríguez Reyna, Carlos Alberto (ORCID: 0000-0003-1671-5273)

LÍNEA DE INVESTIGACIÓN:

Diseño de Infraestructura Vial

TRUJILLO – PERÚ

2022

DEDICATORIA

Este presente trabajo de investigación es dedicado para todos los estudiantes que se esfuerzan día a día para seguir creciendo profesionalmente para posterior a ello ser un aporte para la sociedad.

Edwin Cusi

A mis queridos padres que siempre han estado presentes a lo largo de mi formación, en mis buenas y malas decisiones, siempre serán mi apoyo emocional.

Alex Ticona

AGRADECIMIENTO

A la Universidad César Vallejo por acogernos y ofrecernos la oportunidad de ser profesionales acreditados para ser parte de la solución de los problemas que tiene nuestro país.

A nuestro asesor el Mg. Ing. Carlos Alberto Rodríguez Reyna por su dedicación en cada fin de semana, compartiendo sus conocimientos.

A la Universidad Andina Néstor Cáceres Velásquez que pese a sus muchas dificultades formo parte de nuestra formación.

ÍNDICE DE CONTENIDOS

ÍNDICE DE TABLAS

ÍNDICE DE FIGURAS

RESUMEN

Este trabajo de investigación busca ser una alternativa al problema de captación del agua superficial hacia los sistemas de drenaje derivado de las aguas pluviales en la ciudad de Juliaca, buscando evitar los encharcamientos para permitir la filtración de las aguas pluviales y la vez evitar los daños causados por los vehículos que transitan por las calles, buscando el diseño de un concreto permeable de mayor resistencia al diseño común, a este concreto permeable se añadió plastificante con la finalidad de que disminuya la relación agua/cemento y así se tenga una mayor resistencia a la compresión, este diseño está basado en la norma ACI 522R del 2010.

La presente investigación es del tipo no experimental y el diseño de investigación transversal descriptivo, debido a que se evaluaron los datos a la compresión en momentos determinados como son a los 7, 14 y 28 días, siendo el tipo de muestra no probabilístico, teniendo las probetas agrupadas en dos grupos una muestra patrón y la otra con plastificante.

Se obtuvo un concreto permeable de mayor resistencia al diseño patrón a los 7 días en un 5.75%, a los 14 días en un 6.90% y a los 28 días en un 4.72%. Se realizó una correlación estadística utilizando la prueba estadística de T-Student para validar los resultados obteniendo p-valores mayores a 0.05, por lo que se concluye que la resistencia a la compresión del concreto permeable con añadidura de plastificante no presenta una mejora significativa con respecto a la del diseño patrón debido a que los p-valores son mayores a 0.05.

Palabras clave: diseño de mezcla, concreto permeable, contenido de vacíos, drenaje pluvial, plastificante.

ABSTRACT

This research work seeks to be an alternative to the problem of capturing surface water towards the drainage systems derived from rainwater in the city of Juliaca, seeking to avoid puddles to allow the filtration of rainwater and at the same time avoid the damage caused by the vehicles that travel through the streets, seeking the design of a permeable concrete with greater resistance to the common design, a plasticizer was added to this permeable concrete in order to reduce the water/cement ratio and thus have a greater resistance to compression, this design is based on the 2010 ACI 522R standard.

The present investigation is of the non-experimental type and the descriptive cross-sectional investigation design, due to the fact that the compression data were evaluated at certain moments such as 7, 14 and 28 days, being the type of non-probabilistic sample, having the Specimens grouped into two groups, one standard sample and the other with plasticizer.

A permeable concrete with greater resistance to the standard design was obtained at 7 days in 5.75%, at 14 days in 6.90% and at 28 days in 4.72%. A statistical correlation was carried out using the T-Student statistical test to validate the results, obtaining p-values greater than 0.05, so it is concluded that the compressive strength of pervious concrete with the addition of plasticizer does not present a significant improvement with respect to that of the standard design because the p-values are greater than 0.05.

Keywords: mix design, pervious concrete, void content, storm drainage, plasticizer.

.

I. INTRODUCCIÓN

La ciudad de Juliaca se ubica en la Sierra Sur del país; debido a su relieve y a las precipitaciones de diciembre a marzo, las calles y vías de circulación tanto vehicular y peatonal, se inundan con facilidad formando zonas de estancamiento de agua por lo que, las vías con pavimento flexible se deterioran con facilidad debido a la retención superficial de aguas; actualmente Juliaca no cuenta con un sistema en funcionamiento de drenaje pluvial que pueda evacuar las aguas acumuladas en la ciudad.

Actualmente la construcción del drenaje de la ciudad se encuentra paralizado y se encuentra en proceso la elaboración del expediente de saldo de obra del drenaje pluvial (código cui: 2090887) para la conclusión de dicho proyecto, dicho proyecto considera captaciones menores que conducen a tuberías para luego desembocar en zonas de acumulación temporal fuera de la ciudad. Sobre las vías con pavimento rígido se tiene grandes acumulaciones de agua en diversas partes de la ciudad debido a que el concreto utilizado no es permeable. Los sistemas de canalización y captación existentes no son suficientes por lo que se tiene muchas zonas con acumulación de agua, las cuales desaparecen por la evaporación lenta durante días.

El concreto permeable data de épocas posteriores a la Segunda Guerra Mundial aproximadamente por los años 40, cuando la mayoría de ciudades quedaron destrozadas debido a la guerra por lo que surge la necesidad de crear materiales de construcción de fácil acceso y económicos para la reconstrucción de las ciudades afectadas, se utilizaron parte de los escombros como parte del nuevo material con lo cual se permitía que el agua pudiera escurrirse y no acumularse en la superficie, con lo que el concreto permeable fue una solución en esa situación posguerra.

Con el transcurrir del tiempo, se continuó utilizando este material que debido a su baja resistencia a la compresión se utilizó en estacionamientos, aceras, ciclovías, pases peatonales y otros pavimentos de bajo tránsito, con lo cual se conseguía que la escorrentía superficial sea infiltrada al subsuelo o sea parte de otros sistemas de drenaje.

Instituciones Internacionales como es la Agencia de Protección Ambiental (EPA) considera como un material trascendental al concreto permeable porque permite una adecuada conducción y manejo del agua de lluvia.

El presente trabajo trata sobre el concreto permeable el cual según el ACI-522R (2010, p. 2) menciona que dicho concreto se refiere a la mezcla de cemento portland, agregado grueso, escaso agregado fino, aditivo y agua, la mezcla y combinado de estos materiales nos dará un material compacto con la particularidad de tener una mayor cantidad de vacíos por el agregado grueso que utiliza.

Referenciando a ACI-522R (2010, p. 2), nos indica las particularidades de este concreto permeable el cual nos indica que los poros interconectados están en un intervalo de 2 a 8 mm, el cual posibilita que el agua y otras sustancias fluidas con densidades similares al agua pasen a través de él, el porcentaje de vacíos varía entre 18 y 35%, cuya resistencia a la compresión puede oscilar entre 2.8 a 28 MPa, la velocidad de drenaje varía de acuerdo al tamaño del agregado, pero generalmente esta entre 81 a 730 L/min/m2.

Debido a los problemas contemplados con la evacuación de las aguas pluviales de la ciudad es que se propone el concreto permeable como una opción de solución para reducir las cúspides de escorrentía que son generados por las lluvias, el cual debe ser parte del sistema de drenaje en construcción de la ciudad. Por lo que planteamos el siguiente planteamiento general del problema ¿En qué porcentaje aumenta la resistencia a la compresión del concreto permeable con plastificante? y los problemas específicos son: ¿Cuáles son las características físico – mecánicos de los agregados?, ¿Cuál es la resistencia a la compresión del concreto permeable con y sin adición de plastificante?, ¿Cuál es el contenido de vacíos del concreto permeable?, ¿Cuál es la permeabilidad del concreto permeable?, ¿Cuál es la intensidad de la precipitación para el concreto permeable? y ¿Cuál es la capacidad del sistema de drenaje de aguas pluviales de la ciudad de Juliaca?

La situación de las calles en el periodo de diciembre a marzo en la ciudad de Juliaca es de empozamientos de agua, en varias de las calles pavimentadas y asfaltadas de la ciudad, la tasa de infiltración es muy baja debido a que el concreto no es permeable y no se cuenta con un sistema integral de drenaje que permita su rápida evacuación, además de ello la topografía de la ciudad es plana por lo cual es difícil conducir las aguas por gravedad. El problema de la colmatación de agua en la superficie de las calles y avenidas es cada vez más frecuente debido al crecimiento constante de la ciudad, trayendo consigo que se formen focos infecciosos debido al empozamiento del agua.

En base a lo definido podemos clasificar la justificación en:

Justificación Práctica, utilizando el diseño de mezcla con adición de plastificante se obtendrá un concreto permeable de mayor resistencia que podrá ser aplicado en las calles y avenidas como parte complementaria al sistema de drenaje pluvial de la ciudad, pudiendo construirse cunetas de concreto permeable.

Justificación Teórica, servirá como base para posteriores estudios en la ciudad pudiendo esta ser mejorada y no incurrir en algunas fallas de procedimiento que pudieran cometerse.

Justificación Social, al ser una solución al problema de empozamiento de agua en la ciudad, hará transitable las calles de la ciudad en época de lluvia y evitará que se propague alguna enfermedad debido al empozamiento de agua.

Se formula la siguiente hipótesis: la adición de plastificante al diseño de mezcla del concreto permeable aumenta la resistencia a la compresión como alternativa para el drenaje pluvial en Juliaca 2021, la cual será probada mediante un análisis estadístico.

El propósito principal de este estudio es diseñar un concreto con adición de plastificante para lograr una mayor resistencia a la compresión debido a la disminución de la relación agua-cemento, por lo que plantearemos el siguiente objetivo general de: Evaluar el porcentaje de mejora de la resistencia a la compresión del concreto permeable con la adición de plastificante.

Y los objetivos específicos:

Determinar las características físicas - mecánicas del agregado fino y grueso de la cantera Isla.

Determinar la resistencia a la compresión del concreto permeable con y sin adición de plastificante.

Determinar el contenido de vacíos del concreto permeable.

Determinar la permeabilidad del concreto permeable.

Determinar la intensidad de la precipitación para el concreto permeable.

Analizar la capacidad del sistema de drenaje de aguas pluviales de la ciudad de Juliaca.

II. MARCO TEÓRICO

a. CONCEPTOS, DEFINICIONES Y CONTEXTOS TEÓRICOS.

Los pavimentos permeables existen hace 100 años, sin embargo, se ha iniciado su uso hace unos 40 de una manera más frecuente (Hiriart, 2009, p. 21). Según la Entidad de Protección Ambiental EPA[1] de EE.UU. considera en la actualidad al concreto permeable como una de las Prácticas de Mejor Administración (BMP[2]) para el control de los escurrimientos torrenciales, sobre una base local o regional, (Tennis, Leming y Akers, 2004, p. 9).

Para Moujir y Castañeda (2014, p. 14), egresados de la Universidad Javeriana - Colombia, que desarrollaron el trabajo de investigación titulada

---

[1] Para sus siglas en Ingles EPA (Environmental Protection Agency)

[2] Para sus siglas en Ingles BMP (Best Management Practices)

“Diseño y Aplicación de Concreto Poroso para Pavimentos”. El objetivo principal fue diseñar una mezcla de concreto poroso que sería aplicado en pavimentos del tipo rígido se agruparon en dos grupos para dos tipos de mezcla el primero con agregado fino y el otro sin agregado fino, se compararon sus particularidades de resistencia a la flexión y compresión, elasticidad, porcentaje de vacíos, permeabilidad, al final llegan a la conclusión de cuál es el más adecuado para aplicarlo en la infraestructura vial con lo cual se consigue una disminución del flujo superficial, se complementa con el sistema de drenaje, para que el agua filtrada no afecte el concreto poroso, más específicamente sus propiedades mecánicas.

Por su parte Meneses y Bravo (2007, p. 10), estudiantes egresados de la Universidad de Medellín, elaboran el trabajo de investigación referente a la Resistencia mecánica del concreto poroso y condiciones de obra en los pavimentos según la granulometría del agregado, los cuales realizaron pruebas de resistencia a la compresión del concreto poroso, para la mezcla utilizaron materiales de la región de Antioquia como son los agregados tanto grueso y fino. Al realizar el estudio utilizan agregado grueso con un mínimo de agregado fino, puesto que la adición de mayor agregado fino disminuye la permeabilidad del concreto. Los materiales para la mezcla como los agregados cumplieron ciertas características para que cumpla con los requerimientos del concreto permeable por lo que para conseguir un porcentaje de vacíos entre 13 – 25 % el agregado fino debe poseer un tamaño de 5 mm y de 5 – 25 mm el agregado grueso. La relación a/c optima fue de 0.4 el cual se considera adecuado referenciando a trabajos anteriores.

Los autores Falcon y Baldeon (2016, p. 6), egresados de la Universidad Nacional Hermilio Valdizan, realizaron un proyecto de investigación referente al Diseño de un pavimento permeable rígido para estacionamientos en la ciudad de Huánuco cuyos agregados provenían de la cantera de la zona de Chullqui. Quienes proponen realizar el diseño de un pavimento permeable con agregados de la zona, para ser aplicados en estacionamientos de la ciudad de Huánuco el cual funcionara como parte complementaria del drenaje de la ciudad, se utilizó agregados de la cantera Chullqui a los cuales se realizaron las pruebas físicas y mecánicas para determinar sus características y propiedades, se utilizó un cemento del tipo I.

También los autores Guizado y Curi (2017, p. 3), estudiantes egresados de la Universidad Pontificia Católica del Perú, ejecutaron el trabajo referente a la Evaluación del concreto permeable para la zona de la costa noroeste del Perú en vías urbanas y pavimentos especiales el cual será una alternativa para el control de las aguas pluviales, cuyo objetivo es buscar una alternativa que permita la mitigación de las aguas pluviales resultantes de las precipitaciones intensas. Realizan la prueba al concreto en las calles y lugares seleccionados de la región para lo cual buscan que se combinen los aspectos estructurales, así como los hidráulicos por lo que deben drenar el agua superficial y mantener a la vez la resistencia necesaria, según el uso que se le dé a la vía. Se realiza mediciones de la tracción por flexión y resistencia a la compresión, luego se evalúa los resultados para ser aplicados en las calles, lugares públicos y pavimentos. Los autores concluyen que es factible elaborar concreto permeable que reúna las condiciones y especificaciones de resistencia a la compresión los cuales serán utilizados para la construcción de vías como calles y lugares de transito tanto peatonal y vehicular cumpliendo con la norma de la CE.010.

Los titulados de la Universidad Nacional del Altiplano Flores y Pacompia (2015, p. 21), realizaron la investigación que consiste en el Diseño de mezcla de concreto permeable para la ciudad de Puno a la cual añadieron tiras de plástico para pavimentos con un diseño de f’c 175 kg/cm2. Los autores se plantearon el agregar tiras de plástico (polipropileno) en el diseño de mezcla y posteriormente evaluar el porcentaje de incidencia en las propiedades del concreto. En el estudio se realizaron diferentes diseños con la incorporación de diferentes porcentajes de polipropileno, llegando a la conclusión de que el adicionado de tiras de polipropileno mejora en menor porcentaje de lo estimado las propiedades del concreto como es su resistencia a la compresión.

Por su parte los autores Arteaga y Patiño (2018, p. 41), en su investigación de “Análisis de contenidos de vacíos para el diseño de mezclas con aditivo SikaCem del concreto permeable para pavimentos en Lima del año 2018”, se plantearon utilizar aditivo plastificante con lo cual se plantearon desarrollar un diseño de mezcla mejorado y a la vez precisar el contenido de vacíos del concreto permeable, como objetivos específicos determinan la permeabilidad y como esta varia con el contenido de vacíos, así como también la variación del agregado grueso, la relación a/c ideal, la resistencia a la compresión con las diferentes variaciones y cómo influye la proporción del aditivo para lograr un diseño de mezcla ideal. Llegan a la conclusión que el 18% de vacíos es el adecuado para el diseño de mezcla, puesto que llega a tener la mayor resistencia a la compresión que está en el parámetro de 2.8 a 28 MPA establecida por el ACI y la proporción de aditivo para 18% de vacíos fue de 4.05 kg/cm3.

en su trabajo de titulación Aquino (2021, p. 18) denominado “Diseño de mezcla de concreto permeable para la ciudad de Chiclayo utilizando diferentes porcentajes de aditivo y agregado fino” de la Universidad Santo Toribio de Mogrovejo de la ciudad de Chiclayo. Se propone determinar cómo influye el adicionado de diferentes cantidades de agregado fino y también el agregar aditivo plastificante Sikacem en el concreto permeable, en sus conclusiones llego a determinar que el adicionado de agregado fino en un 15% y 20% incluyendo la utilización de aditivo plastificante Sikacem genera mejores resultados consiguiendo resistencias a la compresión en 11% y la máxima cantidad de aditivo plastificante es de 500 ml.

Adicionalmente Watanabe (2015, p. 25), ha planteado que el pavimento permeable se producirá como una alternativa de escorrentía y menor escorrentía máxima en áreas urbanas donde no se cuente con permeabilidad o carezca de esta. El objetivo de estos sistemas es crear áreas donde el agua ingrese o se almacene y se reduzca la precipitación al aumentar el tiempo de su concentración. Se recomienda su uso en áreas de poco tráfico como estacionamientos, caminos bien iluminados o irregulares y andenes de tren, entre otros, donde el nivel freático está muy por debajo del área de almacenamiento para no afectar o reducir el volumen de almacenamiento.

Concreto Permeable

Se define al concreto permeable como un material que tiene las siguientes características: Slump Cero y cuya mezcla contiene agregado grueso, poca o casi ningún porcentaje de agregado fino, cemento portland, agua y aditivos. La mezcla de estos elementos producirá un material poroso resistente con conductos o poros interrelacionados, el tamaño de los poros está en el rango de 2 a 8 milímetros (0.08 a 0.32 pulgadas), lo cual facilita el paso del agua a través de los conductos del concreto. El tamaño del agregado a utilizar y su densidad influyen en la capacidad de infiltración debido al contenido de vacíos en un concreto permeable, este valor esta generalmente en el rango de 81 a 730 L/min/m2. La resistencia a la compresión debe estar en el intervalo de 2.8 a 28 MPa y su contenido de vacíos debe estar entre el rango de 15 a 35%, ACI 522R (2010, p. 2).

Figura 1: Concreto permeable.

Fuente: https://www.ecocret.com.pe/tipos-de-concreto/concreto-permeable

Componentes del Concreto Permeable

- **Cemento**

El cemento portland es un tipo de cemento hidráulico cuyo uso se da como aglutinante en el concreto permeable, para que la resistencia del concreto elaborado con cemento portland aumente a esta se podría agregar otros materiales, tales como ceniza volante, humo de sílice o escoria granulada.

Si se utiliza mayor cantidad de cemento portland el concreto será más resistente, pero la posibilidad de que disminuya el porcentaje de vacíos es mayor y por lo tanto disminuye la propiedad de infiltración del agua, por eso el ACI 522R-10 recomienda que la cantidad recomendada debe oscilar entre 270 - 415 kg/m3. ACI 522R-10 (2010, p.15).

- **Agregados**

Para el diseño del concreto permeable se usa en mayor proporción el agregado grueso, siendo facultad del especialista considerar uno o varios tamaños, dentro de los más comunes para la obtención de concreto permeable tenemos los tamaños entre ¾" y 3/8" (19 y 9.5mm), pudiendo ser esta de forma redondeada o angular. La cantidad de agregado fino es limitada porque a mayor cantidad se reduce la infiltración de agua y se ve afectado la conexión de los vacíos en el interior del concreto. La ventaja de adicionar agregado fino es que incrementa la resistencia a la compresión, pero a la vez la densidad del concreto permeable, lo cual perjudica la infiltración del agua.

Según el ACI 522R (2010, p. 6) menciona que el agregado grueso debe ser limpio, libre de recubrimientos y duro, se deben evitar los partículas alargadas o escamosas, la calidad del agregado debe ser igual de importante que en el concreto común.

- **Agua Potable**

La calidad del agua es igual de importante que para los concretos convencionales, evitando agentes contaminantes y siendo el agua potable recomendable para el preparado de la mezcla. La relación de a/c recomendable debido a varios estudios es el de 0.40 con el cual se logra una adecuada resistencia del concreto, siendo el rango recomendado entre 0.26 a 0.40 según ACI 522R (2010, p. 13) el uso excesivo de agua llevará a que la pasta de cemento sea drenada y el mismo obstruirá los poros interconectados del concreto permeable.

- **Aditivos**

Los aditivos influyen en el concreto tanto en su estado fresco y endurecido, los aditivos sirven para optimizar o cambiar las peculiaridades del concreto. Se utilizan aditivos del tipo reductor de agua en función de la relación a/c.

También se utiliza en el concreto permeable los aditivos retardantes los cuales son utilizados para el control y estabilización de la hidratación del cemento, generalmente en mezclas rígidas en climas cálidos. También se utiliza como un aditivo lubricante para la descarga del concreto desde una mezcladora como un mixer u otro tipo.

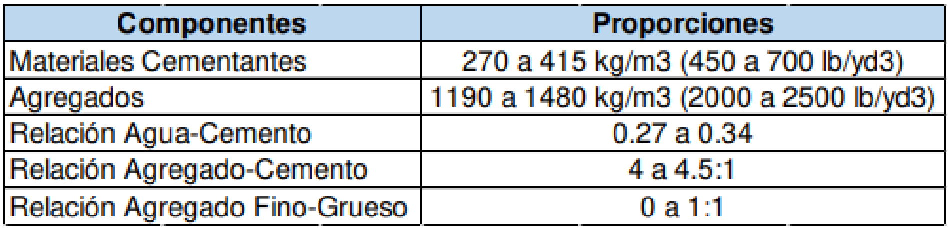
.

En algunas ocasiones en zonas de hielo y deshielo se utilizan los aditivos incorporadores de aire. Los cuales cumplen con la norma ASTM C260, ACI 522R (2010, p. 25)

.

Para una adecuada mezcla o dosificación del concreto permeable el ACI 522R (2010, p. 15) sugiere las siguientes proporciones:

Tabla Nº 1: Componentes y Proporciones sugeridos para el concreto permeable



Componentes	Proporciones
Materiales Cementantes	270 a 415 kg/m3 (450 a 700 lb/yd3)
Agregados	1190 a 1480 kg/m3 (2000 a 2500 lb/yd3)
Relación Agua-Cemento	0.27 a 0.34
Relación Agregado-Cemento	4 a 4.5:1
Relación Agregado Fino-Grueso	0 a 1:1

Fuente: ACI 522R-10 (2010), p. 15

- **Plastificantes y superplastificantes.**

Según Brochure Sika (2020, p. 6) los plastificantes son compuestos orgánicos, los cuales consiguen optimizar el diseño de un concreto disminuyendo la cantidad de agua y cemento para alcanzar las propiedades exigidas para una mejor resistencia.

El plastificante tiene un efecto directo sobre la pasta de cemento y su función es disminuir la viscosidad de la misma. El plastificante tiene la función que la pasta de cemento se vuelva más fluida. Esto se consigue cuando el plastificante recubre las partículas de cemento y genera que las partículas se separen entre ellas, evitando que estas formen conglomerados y así evitar que el agua quede atrapada y se tenga así una mejor distribución del agua. Las partículas al repelerse entre sí, evitan que exista menos fricción y menos resistencia al flujo y así se elimina los micro flóculos.

Por lo tanto, la pasta de cemento fluye más y también el hormigón. En segundo lugar, más concreto fluido puede reducir la cantidad de agua que contiene, alterando así las propiedades de la pasta, con menos agua aumentando su resistencia en este estado.

Indica Brochure Sika (2020, p. 10) los superplastificantes son la evolución tecnológica más radical de los aditivos para hormigón que se ha producido en los superplastificantes en los últimos 20 años. Estos aditivos, tienen funciones similares a los plastificantes, es decir, aumentan la trabajabilidad de la pasta de cemento, mejorando así la trabajabilidad del concreto. Este aumento de trabajabilidad puede reducir el contenido de agua y cemento (son ahorradores de pasta) manteniendo la fluidez y resistencia del material. Una vez que la capacidad del plastificante alcanza su valor máximo, se utiliza el superplastificante. Son particularmente efectivos en concreto de alto asentamiento o de alta resistencia, en ambos casos, el contenido de pasta es alto.

Resistencia a la Compresión

Una de las características del concreto es la resistencia mecánica y como tal la principal característica es la resistencia a la compresión, la cual se define como la capacidad para resistir carga por unidad de área y se enuncia en términos de esfuerzo en unidades como MPa, kg/cm2 y en Psi.

Los pruebas y resultados de la resistencia a compresión son para determinar que el diseño de mezcla utilizada reúna los requerimientos de la resistencia solicitada (f’c) para un determinado tipo de estructura.

Las pruebas de resistencia se realizan elaborando cilindros, los cuales son moldeados en cilindros metálicos con medidas estandarizadas, los cilindros son realizados con la finalidad de determinar la resistencia del concreto, aceptación de cierta dosificación y para llevar el control de calidad del concreto en determinada obra; así como el curado del mismo. El tiempo o edad en que se toman las pruebas son generalmente a los 7,14 y 28 días o de acuerdo a las características de la obra. Un resultado de prueba se considera como aceptable de la media de por lo menos 2 pruebas de resistencia de la manera común, elaborada con el mismo diseño de mezcla y realizadas el mismo día. Cemex.com.pe (2020, párr. 10)

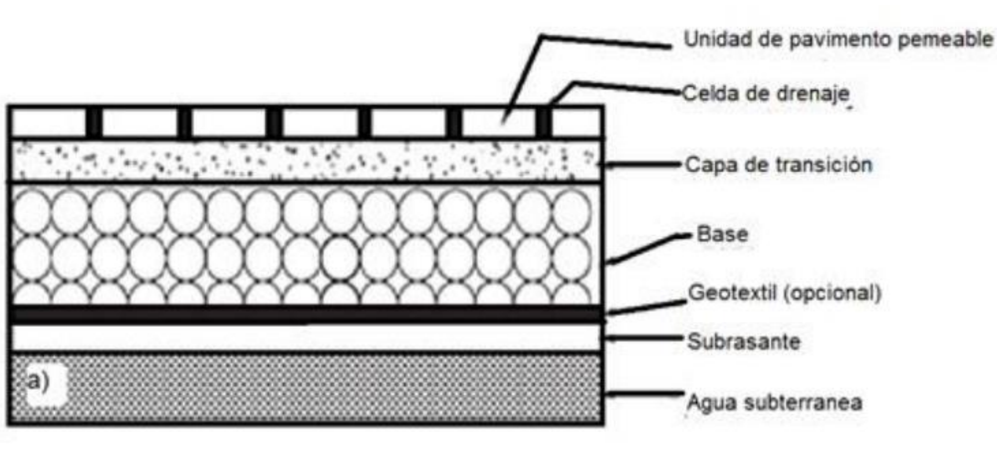
Drenaje Pluvial Urbano

Se denomina así al conjunto de componentes que cumplen la función de recolectar las corrientes de agua superficiales cuando estas desbordan un depósito natural o artificial, las cuales provienen o se originan a partir de las lluvias. Esta escorrentía proviene de las zonas alta y zonas que tienen poca o nula permeabilidad, estos flujos de agua son captados por un cuerpo receptor.

Los puntos a considerar son la capacidad, secciones, el tamaño de la estructura; los elementos a considerar serán según los puntos de vertido, el trazo de colectores, esto será considerando la topografía de la zona.

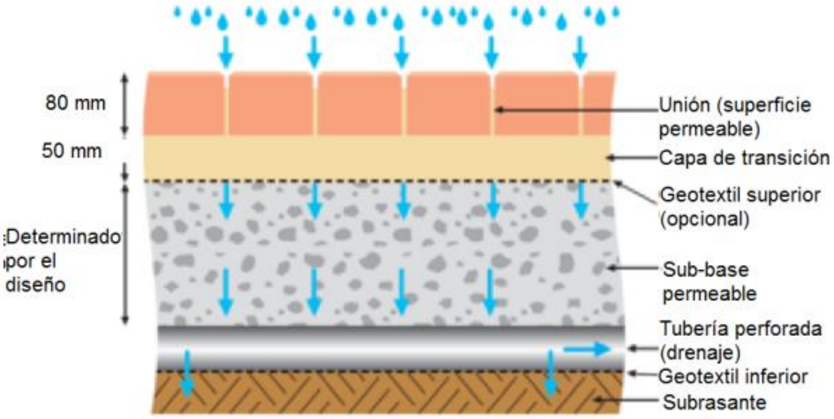
Considerando un diseño de drenaje pluvial en un centro urbano como una ciudad y/o centro poblado con las características mencionadas se podrá garantizar la disminución de los daños que ocasionan las lluvias periódicas en la infraestructura urbana como son las pistas, veredas, diversas edificaciones; así como también permitiendo que los habitantes puedan desarrollar de forma natural sus actividades cotidianas sin tener que ser perjudicados por los aniegos o empozamientos de agua. (Pérez, 2015, p. 6).

Figura 2: Diseño típico de un sistema de pavimento permeable, como parte del sistema de drenaje pluvial



Fuente: Scholz & Grabowiecki (2006, p. 35)

Figura 3: Estructura típica de pavimento permeable



Fuente: Adaptado de Trujillo y Quiroz (2013, p. 56)

III. METODOLOGÍA

Este trabajo de investigación se guía por el **enfoque cuantitativo** porque utiliza la recopilación de datos mediante fichas para ensayar hipótesis basadas en medidas numéricas y análisis estadísticos, con los resultados, esto nos permitirá establecer modelos de comportamiento y probar teorías.. Sampieri (2014, p. 4).

3.1. Tipo y Diseño de Investigación

La investigación es del tipo **no experimental** debido a que no se manipulará intencionalmente las variables y el diseño de investigación es **transversal descriptivo** porque se evaluará la incidencia de la modalidad de una variable al recolectar datos en un momento por lo que se recolectará datos de la compresión a la resistencia a los 7, 14 y 28 días, Sampieri (2014, p. 154).

3.2. Variables y Operacionalización

3.2.1. Variable Independiente (X)

Diseño de concreto permeable con plastificante para mejorar la resistencia a la compresión.

3.2.2. Variable Dependiente (Y)

Drenaje pluvial en Juliaca 2021

	VARIABLE	DEFINICIÓN CONCEPTUAL	DEFINICIÓN OPERACIONAL	DIMENSIÓN	INDICADORES	ESCALA DE MEDICIÓN
INDEPENDIENTE	Diseño de concreto permeable con plastificante para mejorar la resistencia a la compresión.	Concreto de alta porosidad que permite la infiltración del agua al subsuelo o a otro sistema de captación de forma más rápida, compuesto de cemento Portland, mayor cantidad de agregado grueso, poco o ninguna cantidad de agregado fino, algún tipo de aditivo y agua. (ACl 522R-10, 2010, p. 2)	Al diseño de mezcla se agrega un porcentaje de plastificante en relación al peso del cemento de la dosificación, se realiza los ensayos para determinar las características de los materiales; elaborándose dos tipos de mezcla, siendo el primero el diseño patrón sin plastificante y el otro con plastificante, posteriormente se determina la resistencia a la compresión.	Dosificación del concreto permeable	Porcentaje de plastificante, en relación al peso de cemento	(5%).
					Porcentaje de Agregado Fino, en relación al peso del A. Grueso..	(10%)
					Porcentaje de Agregado Grueso, en relación a los parámetros de ACI 522R-10.	(1190 a 1480 kg/m³)
					Cemento Portland, en relación a los parámetros de ACI 522R-10	(270 a 415 kg/m³)
					Agua, Cantidad de agua en relación a agua/cemento ACI 522R-10.	L (relación a/c = 0.26 a 0.45)
				Características físicas – mecánicas de agregados	Análisis granulométrico, - Ensayos según ASTM C 33.	%
					Pesos Unitarios, - Ensayos según ASTM C 29	Kg/ m³
					Resistencia al desgaste, Ensayos según ASTM C 131.	%
				Resistencia a la compresión	Resistencia a la compresión del concreto permeable a los 7d, 14d y 28 días (ASTM C 39).	(29 – 286 kg/cm²)
				Contenido de vacíos	Contenido de vacíos del concreto permeable en estado endurecido (ACI 522R-10).	(15 – 35%)

DEPENDIENTE	Drenaje pluvial en Juliaca 2021	Se considera drenaje pluvial a la evacuación hacia un cuerpo receptor las aguas pluviales que se acumulan sobre un área urbana. Debido a las precipitaciones pluviales y a consecuencia de ello se hace uso de un sistema de drenaje menor para poder evacuar las aguas pluviales en alcantarilladas y también usar los sardineles de las veredas, como conductores de las aguas provenientes de las lluvias. (Norma OS.060, p. 1)	Mediante ensayos se determina el coeficiente de permeabilidad, mediante tablas del Senamhi se determina la Intensidad de la precipitación y mediante un análisis documentario se revisa la capacidad del sistema de drenaje de la ciudad de Juliaca.	Permeabilidad	Permeabilidad del Concreto Permeable mediante la Ley de Darcy, según ensayo de permeabilidad en (ACI 522R-10)	(0.14 – 1.22 cm/s)
				Estudio Hidrológico	Intensidad de la precipitación, tabla para diferentes periodos y retorno – Senamhi	(18.9 – 22.3 mm/hr)
				Unidad Receptora	Capacidad del sistema de drenaje de aguas pluviales – Expediente Técnico del Sistema de Drenaje Pluvial de la Municipalidad de Juliaca.	Análisis Documental

3.3. Población

La población son 30 probetas para las pruebas de compresión axial, donde 3 fueron utilizadas para las pruebas de permeabilidad; Sampieri (2014, p. 174) referencia a Lepkowiski donde indica que “una población es la agrupación de todos los casos que coinciden con una serie de descripciones”, por lo que se considera las probetas elaboradas con dosificación determinada por la normativa ACI 522R-10.

Muestra de Estudio

El tipo de muestra es No Probabilístico porque la elección de las muestras no depende de la probabilidad sino de las características de la investigación, Sampieri (2014, p. 176).

La muestra como tal es un subgrupo de la población, Sampieri (2014, p. 176), nuestros subgrupos en este caso son las probetas agrupadas por características determinadas como los grupos Sin Plastificante y Con Plastificante las cuales se ensayaron a los 7, 14 y 28 días, tomando como muestra 5 unidades de cada tipo con la finalidad de tener una correlación estadística que permita determinar una significancia aceptable determinada por la varianza de las muestras.

3.4. Técnicas e Instrumentos de Recolección de Datos

Técnica: Observación.
Se utiliza la técnica de observación porque nos permite a través de la recopilación de datos sistemático, valido y confiable la caracterización de nuestros elementos de muestra (Sampieri, 2014, p. 399).

Instrumentos: Fichas de recopilación de datos

Para el caso de las muestras de probeta se dispone de fichas estandarizadas de laboratorio validadas por las normas internaciones en los cuales se recolecta la información para luego procesarlas.

3.5. Procedimiento

- Se realiza el muestreo del agregado fino y grueso, cemento y aditivo; para determinar sus características físico-mecánicos.
- Los materiales muestreados se llevan a laboratorio y se realizan los ensayos respectivos.
- Con los datos obtenidos se realiza el diseño de mezcla con las proporciones para cada material.
- Se realiza el muestreo en moldes cilíndricos.
- Se realiza los ensayos a compresión axial, porcentaje de vacíos y permeabilidad, a partir de estos ensayos se evalúan los resultados.

3.6. Método de Análisis de Datos.

El procedimiento será evaluado según la norma ACI 522R-10 (Report on Pervious Concrete, American Concrete Institute) el cual determina los procedimientos y parámetros para la fabricación de concreto permeable.

Los resultados de la prueba de compresión axial serán corroborados mediante la distribución estadística T-student para establecer si existe una diferencia significativa entre los dos grupos de nuestros ensayos de compresión.

3.7. Aspectos éticos.

Los autores de este trabajo de investigación son responsables del trabajo presentado y de cada uno de los procedimientos realizados. Se ha respetado a cada uno de los autores los cuales fueron citados y se sometió el presente documento por el software Turnitin para verificación de similitud.

IV. RESULTADOS

4.1. Diseño de Mezcla Concreto Permeable

Datos Iniciales
Norma: ACI 522R-10: “Reporte en Concreto Poroso”

Materiales.

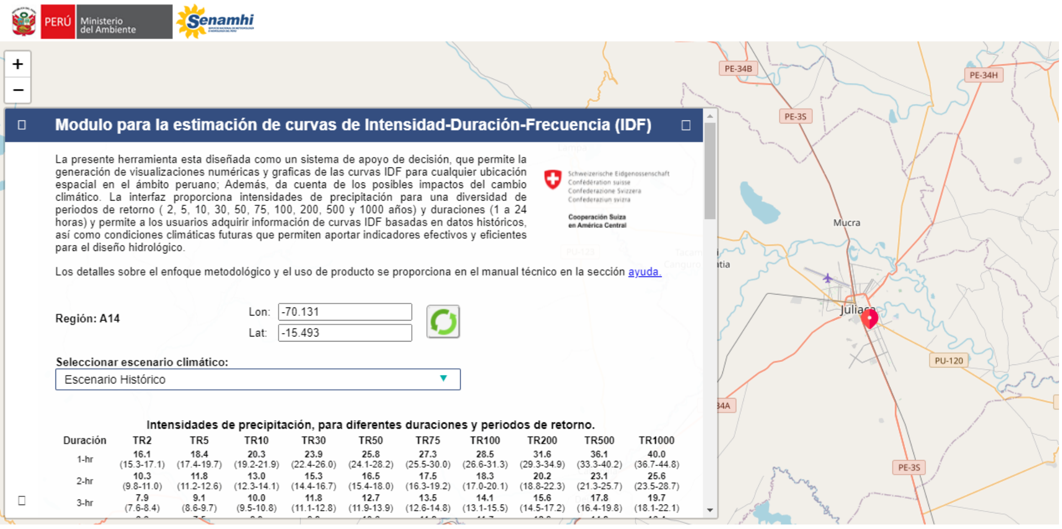
- **Agregado:** Zona Cantera Isla (Cantera propiedad de la Comunidad de Isla)
- **Cemento:** Rumi - Tipo I Portland
- **Agua:** Potable de uso común de la ciudad de Juliaca
- **Agregado Fino:** 10%

MATERIAL	PESO ESPECIFICO (gr/cm3)	MODULO FINEZA	TAMAÑO MAX. NOMINAL	HUMEDAD %	ABSORCIÓN %	P. UNITARIO SUELTO (kg/m3)	P. UNITARIO COMPACT. (kg/m3)
CEMENTO RUMI - TIPO I	2.82						
AGREGADO FINO	2.55	3.34		3.99	2.76	1586	1644
AGREGADO GRUESO	2.53		3/4"	2.89	1.72	1472	1556
ADITIVO - PLASTIFICANTE	1.20						
AGUA	1.00						

Procedimiento:

- **Análisis Hidrológico:** Según el módulo para la estimación de curvas de intensidad – Duración – Frecuencia (IDF) del Senamhi:

Figura 4: Módulo de curva Intensidad – Duración - Frecuencia



Modulo para la estimación de curvas de Intensidad-Duración-Frecuencia (IDF)

La presente herramienta esta diseñada como un sistema de apoyo de decisión, que permite la generación de visualizaciones numéricas y graficas de las curvas IDF para cualquier ubicación espacial en el ámbito peruano; Además, da cuenta de los posibles impactos del cambio climático. La interfaz proporciona intensidades de precipitación para una diversidad de periodos de retorno (2, 5, 10, 30, 50, 75, 100, 200, 500 y 1000 años) y duraciones (1 a 24 horas) y permite a los usuarios adquirir información de curvas IDF basadas en datos históricos, así como condiciones climáticas futuras que permiten aportar indicadores efectivos y eficientes para el diseño hidrológico.

Los detalles sobre el enfoque metodológico y el uso de producto se proporciona en el manual técnico en la sección ayuda.

Región: A14

Lon: -70.131

Lat: -15.493

Seleccionar escenario climático: Escenario Histórico

Intensidades de precipitación, para diferentes duraciones y periodos de retorno.

Duración	TR2	TR5	TR10	TR30	TR50	TR75	TR100	TR200	TR500	TR1000
1-hr	**16.1** (15.3-17.1)	**18.4** (17.4-19.7)	**20.3** (19.2-21.9)	**23.9** (22.4-26.0)	**25.8** (24.1-28.2)	**27.3** (25.5-30.0)	**28.5** (26.6-31.3)	**31.6** (29.3-34.9)	**36.1** (33.3-40.2)	**40.0** (36.7-44.8)
2-hr	**10.3** (9.8-11.0)	**11.8** (11.2-12.6)	**13.0** (12.3-14.1)	**15.3** (14.4-16.7)	**16.5** (15.4-18.0)	**17.5** (16.3-19.2)	**18.3** (17.0-20.1)	**20.2** (18.8-22.3)	**23.1** (21.3-25.7)	**25.6** (23.5-28.7)
3-hr	**7.9** (7.6-8.4)	**9.1** (8.6-9.7)	**10.0** (9.5-10.8)	**11.8** (11.1-12.8)	**12.7** (11.9-13.9)	**13.5** (12.6-14.8)	**14.1** (13.1-15.5)	**15.6** (14.5-17.2)	**17.8** (16.4-19.8)	**19.7** (18.1-22.1)

Fuente: Página web Senamhi (https://idesep.senamhi.gob.pe/dhi-idf/)

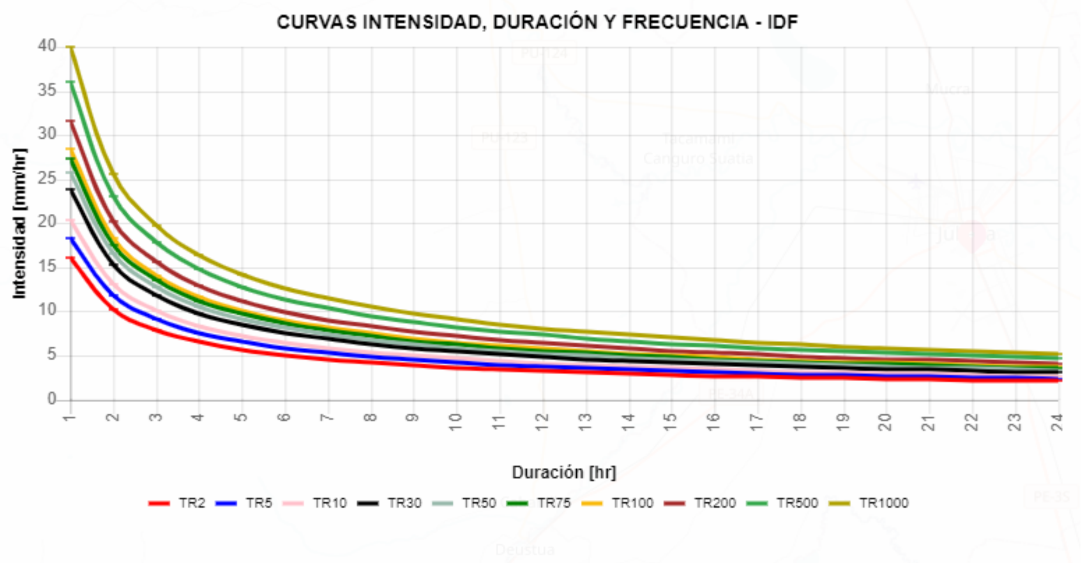
Tabla 1: Intensidad de precipitación para diferentes periodos de retorno y duraciones.

Intensidades de precipitación, para diferentes periodos de retorno y duraciones.				
Duración	**TR2**	**TR5**	**TR10**	**TR30**
1-hr	**16.1**(15.1-17.6)	**18.4**(17.2-20.1)	**20.3**(18.9-22.3)	**23.8**(22.1-26.1)
2-hr	**10.3**(9.7-11.2)	**11.8**(11.0-12.9)	**13.0**(12.1-14.3)	**15.2**(14.1-16.7)
3-hr	**8.0**(7.5-8.7)	**9.1**(8.5-9.9)	**10.0**(9.3-11.0)	**11.7**(10.9-12.9)
4-hr	**6.6**(6.2-7.2)	**7.5**(7.1-8.2)	**8.3**(7.8-9.1)	**9.8**(9.0-10.7)
5-hr	**5.7**(5.4-6.2)	**6.5**(6.1-7.1)	**7.2**(6.7-7.9)	**8.4**(7.8-9.3)
6-hr	**5.1**(4.8-5.6)	**5.8**(5.4-6.4)	**6.4**(6.0-7.0)	**7.5**(7.0-8.3)
7-hr	**4.6**(4.3-5.0)	**5.3**(4.9-5.8)	**5.8**(5.4-6.4)	**6.8**(6.3-7.5)
8-hr	**4.2**(4.0-4.6)	**4.8**(4.5-5.3)	**5.3**(5.0-5.8)	**6.2**(5.8-6.9)
9-hr	**3.9**(3.7-4.3)	**4.5**(4.2-4.9)	**4.9**(4.6-5.4)	**5.8**(5.4-6.4)
10-hr	**3.7**(3.4-4.0)	**4.2**(3.9-4.6)	**4.6**(4.3-5.1)	**5.4**(5.0-6.0)
11-hr	**3.5**(3.2-3.8)	**3.9**(3.7-4.3)	**4.3**(4.1-4.8)	**5.1**(4.7-5.6)
12-hr	**3.3**(3.1-3.6)	**3.7**(3.5-4.1)	**4.1**(3.8-4.5)	**4.8**(4.5-5.3)
13-hr	**3.1**(2.9-3.4)	**3.5**(3.3-3.9)	**3.9**(3.6-4.3)	**4.6**(4.2-5.0)
14-hr	**3.0**(2.8-3.2)	**3.4**(3.2-3.7)	**3.7**(3.5-4.1)	**4.4**(4.0-4.8)
15-hr	**2.8**(2.7-3.1)	**3.2**(3.0-3.5)	**3.6**(3.3-3.9)	**4.2**(3.9-4.6)
16-hr	**2.7**(2.5-3.0)	**3.1**(2.9-3.4)	**3.4**(3.2-3.7)	**4.0**(3.7-4.4)
17-hr	**2.6**(2.5-2.8)	**3.0**(2.8-3.3)	**3.3**(3.1-3.6)	**3.8**(3.6-4.2)
18-hr	**2.5**(2.4-2.7)	**2.9**(2.7-3.1)	**3.2**(3.0-3.5)	**3.7**(3.4-4.1)
19-hr	**2.4**(2.3-2.6)	**2.8**(2.6-3.0)	**3.1**(2.9-3.4)	**3.6**(3.3-3.9)

20-hr	**2.4**(2.2-2.6)	**2.7**(2.5-2.9)	**3.0**(2.8-3.2)	**3.5**(3.2-3.8)
21-hr	**2.3**(2.1-2.5)	**2.6**(2.4-2.8)	**2.9**(2.7-3.1)	**3.4**(3.1-3.7)
22-hr	**2.2**(2.1-2.4)	**2.5**(2.4-2.8)	**2.8**(2.6-3.1)	**3.3**(3.0-3.6)
23-hr	**2.1**(2.0-2.3)	**2.5**(2.3-2.7)	**2.7**(2.5-3.0)	**3.2**(2.9-3.5)
24-hr	**2.1**(2.0-2.3)	**2.4**(2.2-2.6)	**2.6**(2.5-2.9)	**3.1**(2.9-3.4)

Fuente: Pagina web Senamhi (https://idesep.senamhi.gob.pe/dhi-idf/)

Figura 5 : Curva Intensidad, Duración y Frecuencia - IDF



Fuente: Pagina web Senamhi (https://idesep.senamhi.gob.pe/dhi-idf/)

Según la tabla de intensidad de precipitaciones tenemos para un TR10 (periodo de retorno de 10 años) con una duración de 1 hora, se tiene una Intensidad de lluvia de 20.3 mm/hr.

Teniendo en cuenta la capacidad de infiltración del concreto y teniendo en cuenta el factor de rendimiento se tiene que la Intensidad de lluvia es de 203.0 mm/hr.

Por lo tanto, la filtración requerida es de 203.0 mm/h

- **Porcentaje de Vacíos:** Según ACI-522R (2010, p. 2) el contenido de vacíos fluctua entre 18 y 35%, para nuestro caso se calculará de acuerdo a la filtración requerida.

Figura 6: Curva de Relación Porcentaje de vacíos vs Filtración

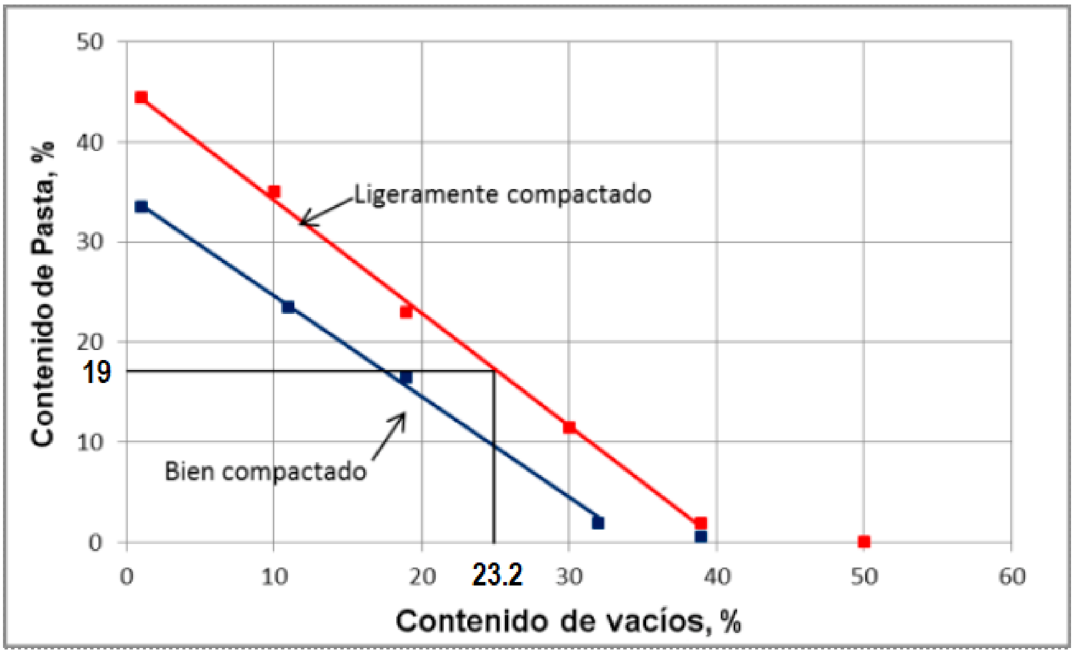
Fuente: adaptado de ACI-522R (2010)

Utilizando la relación Contenido de Vacíos / Filtración, para una filtración de 203 mm/h se tiene un porcentaje de vacíos de 23.2%.

- **Relación agua – cemento a/c:** Según la norma ACI-522R (2010, p.6) indica que el concreto permeable debe ser dosificado con una relación a/c relativamente baja entre 0.26 a 0.40, en nuestro caso utilizaremos la relación a/c de 0.40.

- **Porcentaje de Pasta:**

Figura 7: Relación contenido de vacíos vs contenido de pasta



Fuente: adaptado de ACI-522R (2010)

La compactación requerida para el concreto permeable es Ligeramente Compactado debido a que a mayor compactación se reducirá el contenido de vacíos, además se añadió agregado fino en un 10% es por ello que el porcentaje de pasta se redujo en un 1% quedando el porcentaje de pasta en 18%.

Tenemos:

VolumenPasta = VolumenCemento + VolumenAgua

$$VPasta = \frac{c}{PEcemento} + \frac{a}{PEagua}$$

Dónde:

c: Cemento en peso por m3.

a: Agua en peso por m3

PEcemento = 2.82 gr/cm3

PEagua = 1.00 gr/cm3

$$VPasta = \frac{c}{2.82\ x\ 1000} + \frac{a}{1.00\ x\ 1000}$$

Y reemplazando la relación a/c

$$VPasta = \frac{c}{2.82\ x\ 1000} + \frac{\frac{a}{c} x\ c}{1.00\ x\ 1000}$$

Reemplazando:

$$0.18 = \frac{c}{2.82 *\ 1000} + \frac{0.40 *\ c}{1.00 *\ 1000}$$

Obtenemos:

c = 238.53 kg

$$0.18 = \frac{238.53}{2.82 *\ 1000} + \frac{a}{1.00 *\ 1000}$$

a = 95.41 kg

- **Cálculo de los Volúmenes Absolutos:**

Tabla 2: Calculo de Volúmenes Absolutos

	Peso SSS (kg)	**P.E. (kg/m3)**	**Volumen (m3)**
CEMENTO	238.53	2820	0.085
AGUA	95.41	1000	0.095
PLASTIFICANTE	4.77	1200	0.004
VACÍO			0.232
		Parcial	**0.416**
A. GRUESO			0.584
		Total	**1.000**

Fuente: E. Propia

Adicionando el 10% de agregado fino

Tabla 3: Calculo del 10% del Agregado Fino añadido.

	Peso SSS (kg)	**P.E. (kg/m3)**	**Volumen (m3)**
AG. GRUESO	1329.83	2540	0.526
AG. FINO	148.93	2550	0.058

Fuente: E. Propia

Tabla 4: Cálculo de los Volúmenes Absolutos, incluido el 10% de agregado fino

	Peso SSS (kg)	**P.E. (kg/m3)**	**Volumen (m3)**
CEMENTO	238.53	2820	0.085
AG. GRUESO	1329.83	2530	0.526
AG. FINO	148.93	2550	0.058
PLASTIFICANTE	11.93	1200	0.004
AGUA	95.41	1000	0.095
VACÍO			0.232
		Total	**1.000**

Fuente: E. Propia

- **Diseño Corregido por Humedad:**

Tabla 5: Cantidades corregidas por humedad.

	Cantidad	
CEMENTO	238.53	kg/m3
A. FINO	149.33	kg/m3
A. GRUESO	1321.06	kg/m3
PLASTIFICANTE	11.93	kg/m3
AGUA	103.78	kg/m3

Fuente: E. Propia

- **Cantidades de Diseño de Mezcla (Peso):**

Tabla 6: Proporciones de diseño de mezcla

	Cantidad	
CEMENTO	1	
A. FINO	0.62	
A. GRUESO	5.58	
PLASTIFICANTE	0.02	
AGUA	17.00	lt.

Fuente: E. Propia

4.2. Características físicas - mecánicas del agregado fino y grueso de la cantera Isla.

Tabla 7: Granulometría del agregado fino

GRANULOMETRÍA - AGREGADO FINO

TAMICES ASTM	ABERTURA mm	PESO RETENIDO en gramos (b)	% RETENIDO (c)=(b)/(a)*100	% RETENIDO ACUMUL. (d)=SUMA (c)	% PASANTE ACUMUL. 100 - (d)
3"	76.200	-	-	-	
2 1/2"	63.500	-	-	-	
2"	50.600	-	-	-	
1 1/2"	38.100	-	-	-	
1"	25.400	-	-	-	
3/4"	19.050	-	-	-	
1/2"	12.700	-	-	-	100.00
3/8"	9.525	-	-	-	100.00
1/4"	6.350	-	-	-	
# 4	4.760	-	-	-	100.00
# 8	2.380	140.12	28.02	28.02	71.98
# 10	2.000	-	-	-	-
# 16	1.190	120.40	24.08	52.10	47.90
# 20	0.840	-	-	-	-
# 30	0.590	95.25	19.05	71.15	28.85
# 40	0.420	-	-	-	-
# 50	0.300	79.92	15.98	87.14	12.86
# 60	0.250	-	-	-	-
# 80	0.180	-	-	-	-

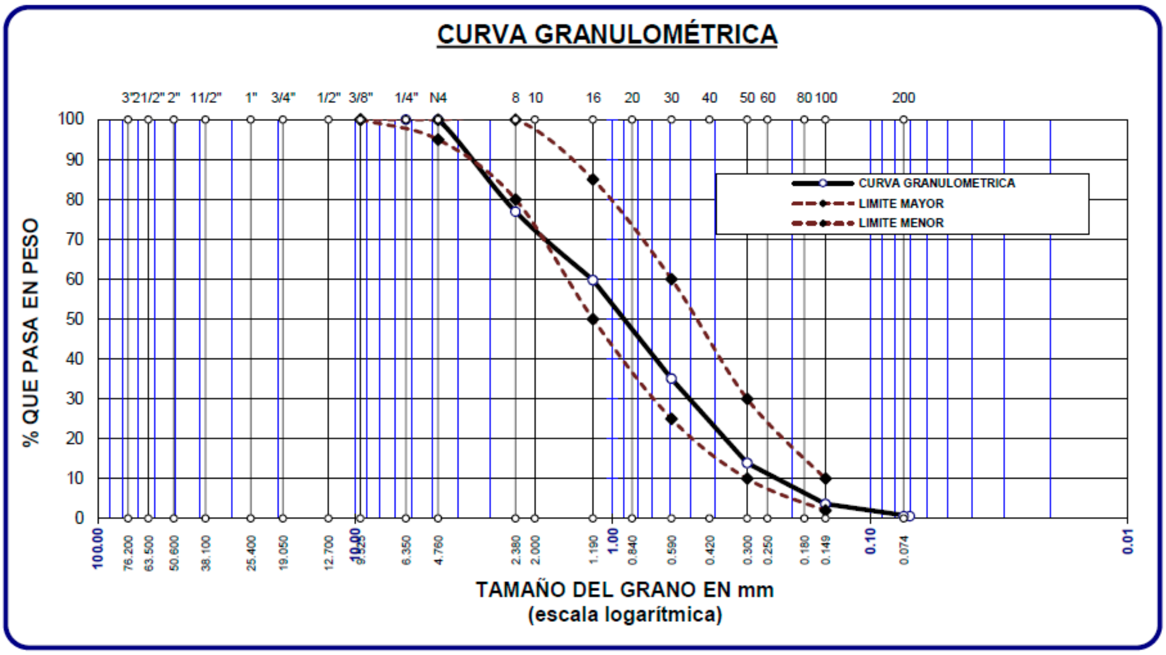
#100	0.149	44.59	8.92	96.06	3.94
#200	0.074	11.94	2.39	98.44	1.56
BASE		**7.78**	**1.56**	**100.00**	**0.00**
TOTAL (a)		**500.0**	**100.0**		
% PERDIDA		**1.56%**			

Módulo de Fineza = 3.34

Fuente: E. Propia

Se tiene un agregado fino con material retenido en las mallas #8, #16, #30, #50, #100, # 200.

Figura 8: Curva de tamizado - agregado fino



Fuente: E. Propia

Tabla 8: Granulometría - agregado grueso.

GRANULOMETRÍA - AGREGADO GRUESO

		PESO	%	%	%

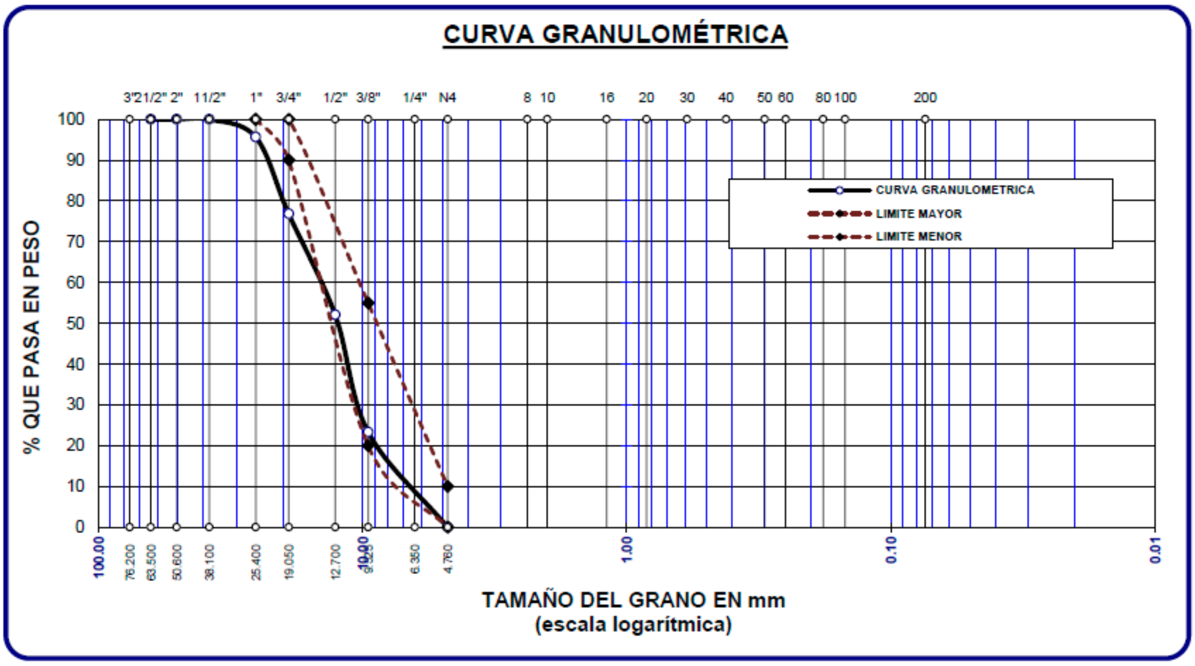
TAMICES ASTM	**ABERTURA mm**	**RETENIDO**	**RETENIDO**	**RETENIDO**	**PASANTE**
		en gramos		**ACUMUL.**	**ACUMUL.**
		(b)	**(c)=(b)/(a)*100**	**(d)=SUMA (c)**	**100 - (d)**
3"	76.200	-	-	-	-
2 1/2"	63.500	-	-	-	100.0
2"	50.600	-	-	-	100.0
1 1/2"	38.100	-	-	-	100.0
1"	25.400	1550	4.43	4.43	95.57
3/4"	19.050	582.0	16.63	21.06	78.94
1/2"	12.700	981.0	28.03	49.09	50.91
3/8"	9.525	769.0	21.97	71.06	28.94
1/4"	6.350	-	-	-	-
# 4	4.760	1013.0	28.94	100.0	0.00
# 8	2.380	-	-	-	-
# 10	2.000	-	-	-	-
# 16	1.190	-	-	-	-
# 20	0.840	-	-	-	-
# 30	0.590	-	-	-	-
# 40	0.420	-	-	-	-
# 50	0.300	-	-	-	-
# 60	0.250	-	-	-	-
# 80	0.180	-	-	-	-
#100	0.149	-	-	-	-
#200	0.074	-	-	-	-
BASE		-	0.00	0	0.00
TOTAL (a)		3,500.0	100.0		
% PERDIDA		0.00%			

Tamaño max. Nominal = 3/4"

Fuente: E. Propia

Se tiene un agregado grueso con material retenido en las mallas de 1”, ¾”, ½”, 3/8” y #4.

Figura 9: Curva de tamizado del agregado fino



Fuente: E. Propia

Tabla 9: Peso Unitario Suelto - Agregado Fino

PESO UNITARIO SUELTO	RESULTADOS		
	M1	M2	M3
PESO MOLDE	5970 gr	5970 gr	5970 gr
VOLUMEN MOLDE	2163 cm3	2163 cm^3	2163 cm^3
MUESTRA A MOLDE	CAÍDA LIBRE		
PESO MOLDE + MUESTRA SUELTA	9415.00 gr	9385.00 gr	9405.00 gr
PESO MUESTRA SUELTA	3445.00 gr	3415.00 gr	3435.00 gr
DENSIDAD MÍNIMA MUESTRA SECA	**1.593 gr/cm^3**	**1.579 gr/cm^3**	**1.588 gr/cm^3**
PROMEDIO	**1.586 gr/cm^3**		

Fuente: E. Propia

Tabla 10: Peso Unitario Compactado - Agregado Fino

PESO UNITARIO SUELTO	**RESULTADOS**		
	M1	**M2**	**M3**
PESO DE MOLDE	5970 gr	5970 gr	5970 gr
VOLUMEN MOLDE	2163 cm^3	2163 cm^3	2163 cm^3
NRO. CAPAS	3	3	3
NRO. GOLPES x CAPA	25	25	25
PESO DE MOLDE + MUESTRA COMPACTADA	9520.00 gr	9565.00 gr	94995.00 gr
PESO MUESTRA COMPACTADO	3550.00 gr	3595.00 gr	3525.00 gr
DENSIDAD MÍNIMA MUESTRA SECA	**1.641 gr/cm^3**	**1.662 gr/cm^3**	**1.630 gr/cm^3**
PROMEDIO		**1.644 gr/cm^3**	

Fuente: E. Propia

Tabla 11: Peso Unitario Suelto del Agregado Grueso

PESO UNITARIO SUELTO	**RESULTADOS**		
	M1	**M2**	**M3**
PESO DEL MOLDE	7205 gr	7205 gr	7205 gr
VOLUMEN MOLDE	3383 cm^3	3383 cm^3	3383 cm^3
MUESTRA A MOLDE (COLOCACIÓN)		CAÍDA LIBRE	

PESO DEL MOLDE + MUESTRA SUELTA	12205.00 gr	12165.00 gr	12180.00 gr
PESO DE MUESTRA SUELTA	5000.00 gr	4960.00 gr	4975.00 gr
DENSIDAD MÍNIMA - MUESTRA SECA	**1.478 gr/cm^3**	**1.466 gr/cm^3**	**1.471 gr/cm^3**
PROMEDIO		**1.472 gr/cm^3**	

Fuente: E. Propia

Tabla 12: Peso Unitario Compactado del Agregado Grueso

PESO UNITARIO SUELTO	**RESULTADOS**		
	M1	**M2**	**M3**
PESO DEL MOLDE	7205 gr	7205 gr	7205 gr
VOLUMEN DE MOLDE	3383 cm^3	3383 cm^3	3383 cm^3
NRO. DE CAPAS	3	3	3
NRO. GOLPES POR CAPA	25	25	25
PESO DEL MOLDE + MUESTRA COMPACTADA	12445.00 gr	12490.00 gr	12475.00 gr
PESO DE MUESTRA COMPACTADO	5240.00 gr	5285.00 gr	5270.00 gr
DENSIDAD MÍNIMA - MUESTRA SECA	**1.549 gr/cm^3**	**1.562 gr/cm^3**	**1.558 gr/cm^3**
PROMEDIO		**1.556 gr/cm^3**	

Fuente: E. Propia

Tabla 13: Abrasión Los Ángeles

TIPO DE AGREGADO: FINO: ☐ GRUESO: ☒ OTROS: ☐

MUESTRA OBTENIDA POR: CUARTEO: ☐ DIVISOR DE MUESTRAS: ☐

NUMERO DE REVOLUCIONES: 500 ☒ 1000 ☐

CARGA ABRASIVA: 12 ESFERAS

PESO SECO INICIAL MUESTRA: Wi = 5000 gr.

PESO SECO FINAL RETENIDA EN EL CEDAZO Nº 12: Wf = 3709 gr.

PESO DEL MATERIAL QUE PASA EL CEDAZO Nº 12: 1291 gr.

PORCENTAJE DE PERDIDA: De = $\frac{W_i - W_F}{W_i} x\ 100$

De = **25.82%**

Fuente: E. Propia

4.3. Resistencia a compresión del concreto permeable con y sin adición de plastificante.

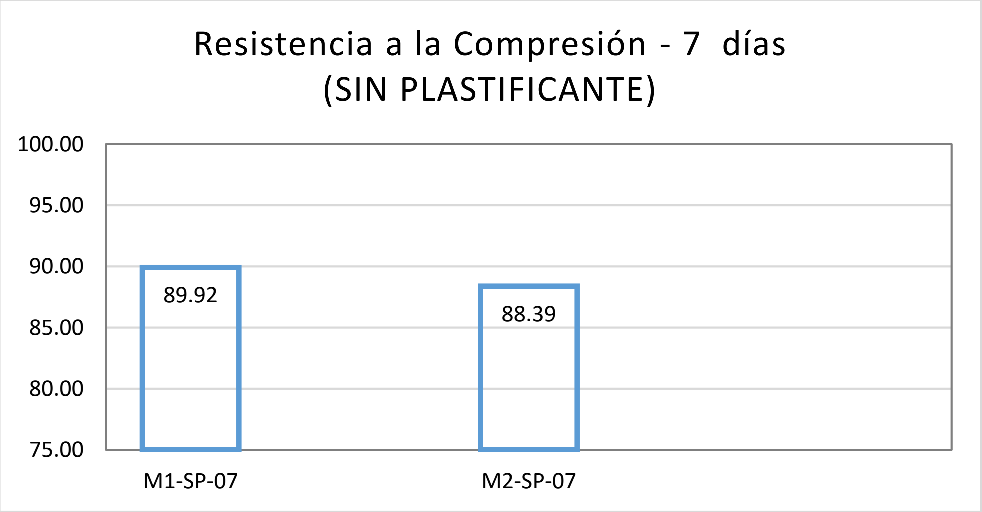
- Resistencia a la compresión - 7 días

Tabla 14: Ensayo de Resistencia a la compresión - 7 días.

ID	TIPO	f'c (kg/cm2)	f'c promedio (kg/cm^2)
M1-SP-07	Diseño Patrón	89.14	89.92
M2-SP-07	Diseño Patrón	90.70	
M3-SP-07	Diseño Patrón	91.12	88.39
M4-SP-07	Diseño Patrón	83.85	
M5-SP-07	Diseño Patrón	90.19	
M1-CP-07	**Con Plastificante**	**97.65**	**95.88**
M2-CP-07	**Con Plastificante**	**94.10**	
M3-CP-07	**Con Plastificante**	**96.91**	**93.30**
M4-CP-07	**Con Plastificante**	**87.35**	
M5-CP-07	**Con Plastificante**	**95.65**	

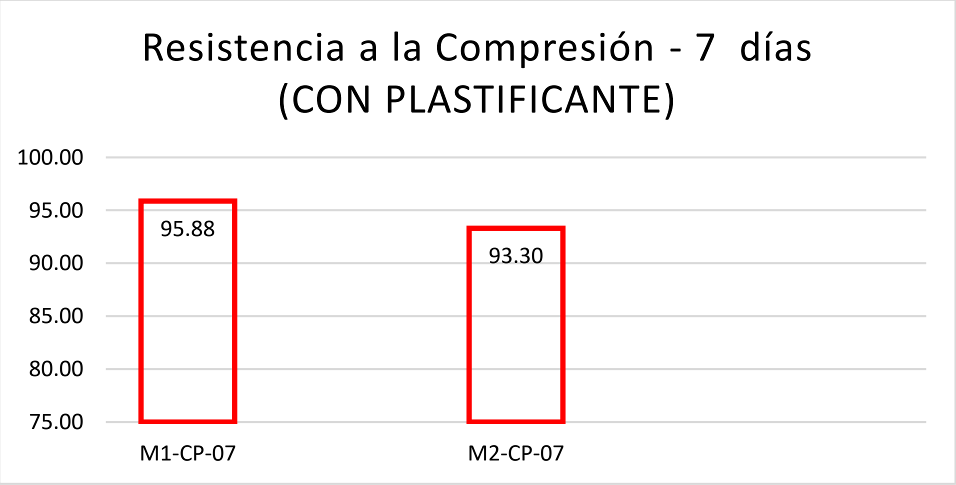
Fuente: E. Propia

Figura 10: Histograma de resistencia a la compresión (kg/cm2) diseño patrón - 7 días.



Fuente: E. Propia

Figura 11: Histograma de resistencia a la compresión (kg/cm2) con plastificante - 7 días.



Fuente: E. Propia

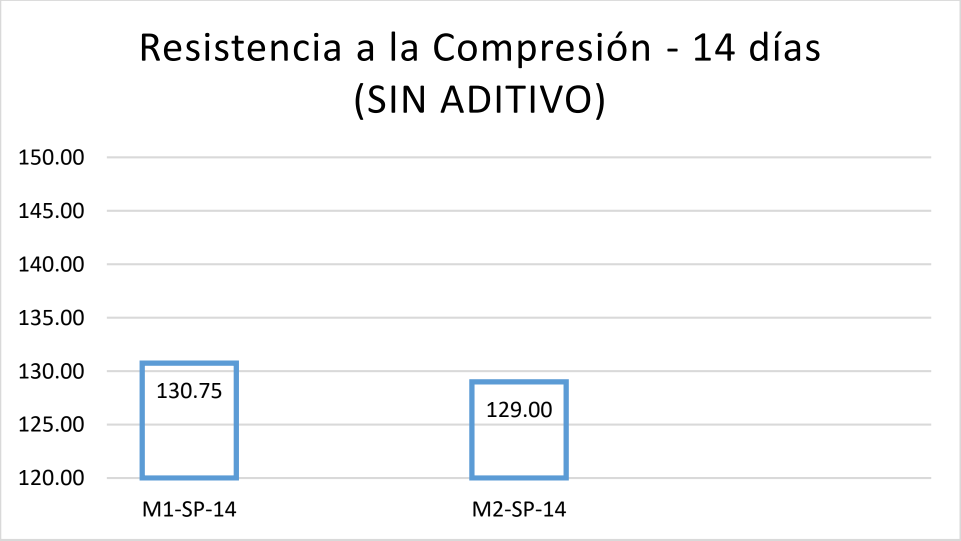
- Resistencia a la compresión - 14 días

Tabla 15: Resistencia a la compresión - 14 días.

ID	TIPO	f'c (kg/cm2)	f'c promedio (kg/cm^2)
M1-SP-14	Diseño Patrón	131.64	130.75
M2-SP-14	Diseño Patrón	129.86	
M3-SP-14	Diseño Patrón	118.04	129.00
M4-SP-14	Diseño Patrón	135.36	
M5-SP-14	Diseño Patrón	133.61	
M1-CP-14	**Con Plastificante**	**138.76**	**142.54**
M2-CP-14	**Con Plastificante**	**146.32**	
M3-CP-14	**Con Plastificante**	**131.25**	**136.46**
M4-CP-14	**Con Plastificante**	**141.26**	
M5-CP-14	**Con Plastificante**	**136.88**	

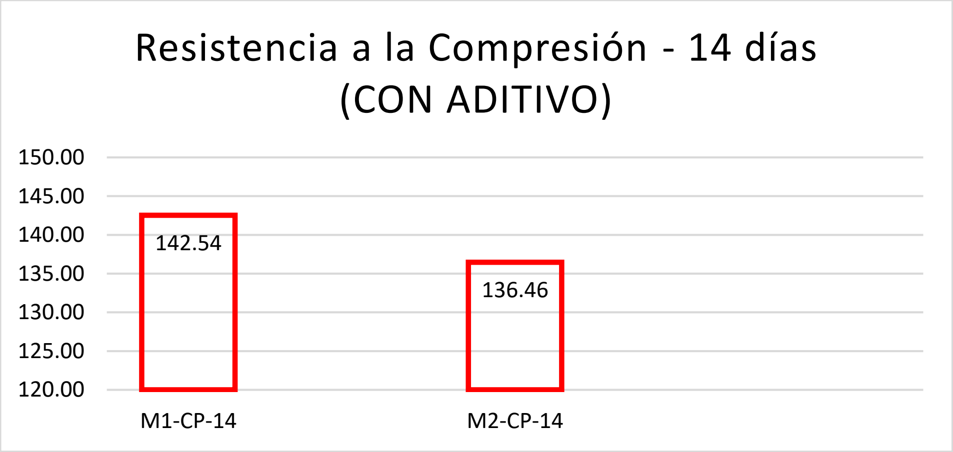
Fuente: E. Propia

Figura 12: Histograma de resistencia a la compresión (kg/cm2) diseño patrón - 14 días.



Fuente: E. Propia

Figura 13: Histograma de resistencia a la compresión (kg/cm2) con plastificante - 14 días.



Fuente: E. Propia

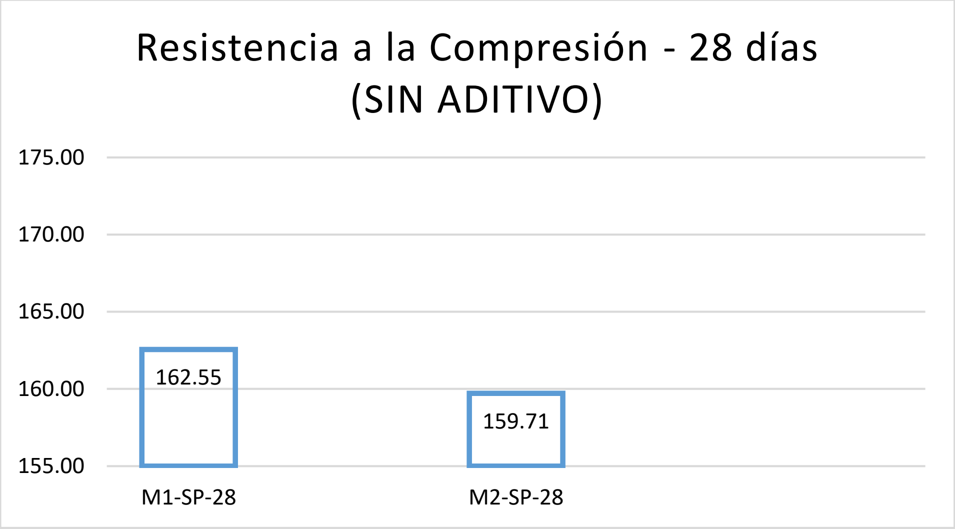
- <u>Resistencia a la compresión - 28 días</u>

Tabla 16: Resistencia a la compresión - 28 días.

ID	TIPO	f'c (kg/cm2)	f'c promedio (kg/cm²)
M1-SP-28	Diseño patrón	158.28	162.55
M2-SP-28	Diseño patrón	166.82	
M3-SP-28	Diseño patrón	161.97	159.71
M4-SP-28	Diseño patrón	165.62	
M5-SP-28	Diseño patrón	151.54	
M1-CP-28	**Con Plastificante**	**169.76**	**171.32**
M2-CP-28	**Con Plastificante**	**172.88**	
M3-CP-28	**Con Plastificante**	**167.84**	**166.91**
M4-CP-28	**Con Plastificante**	**161.75**	
M5-CP-28	**Con Plastificante**	**171.13**	

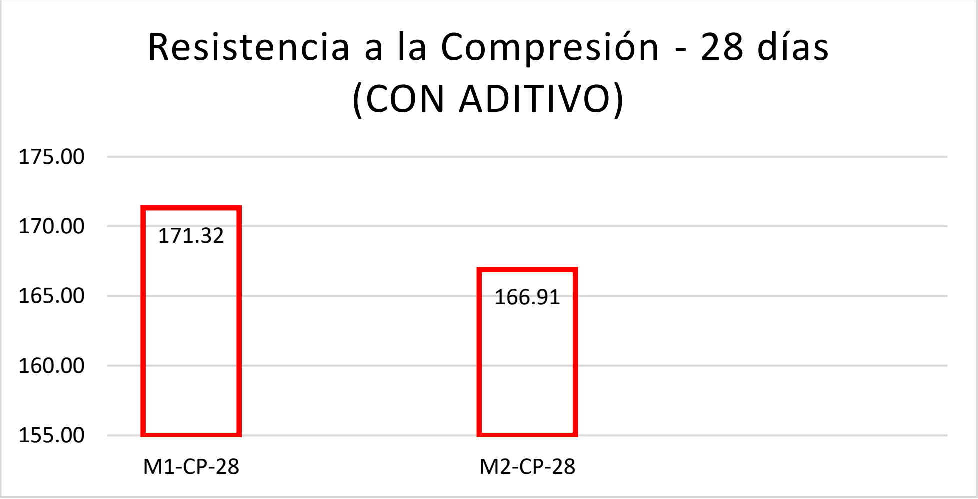
Fuente: E. Propia

Figura 14: Histograma de resistencia a la compresión (kg/cm2) diseño patrón - 28 días.



Fuente: E. Propia

Figura 15: Histograma de resistencia a la compresión (kg/cm2) con plastificante - 28 días.



Fuente: E. Propia

4.4. Contenido de vacíos del concreto permeable en estado endurecido.

Se realizo la prueba del contenido de vacíos en estado endurecido, con las probetas superficialmente secas.

Tabla 17: Cálculo de contenido de vacíos.

DESPLAZAMIENTO DE VOLUMEN	M1-CP-28	M3-CP-28	M5-CP-28
Volumen inicial (Vi)	3000.00 ml	3000.00 ml	3000.00 ml
Volumen final (Vf)	4350.00 ml	4370.00 ml	4335.00 ml
PROBETA	**M1-CP-28**	**M3-CP-28**	**M5-CP-28**
Diámetro sup. de probeta	14.98 cm	15.04 cm	15.06 cm
Diámetro inf. de probeta	15.03 cm	15.01 cm	15.04 cm
Promedio de diámetro de probeta (D)	15.01 cm	15.03 cm	15.05 cm
Altura de probeta (h)	30.04 cm	30.12 cm	30.07 cm
RESULTADOS	**M1-CP-28**	**M3-CP-28**	**M5-CP-28**
Volumen de la probeta - sin espacios vacíos (Vsv).......Vf-Vi	1350.00 cm3	1370.00 cm3	1335.00 cm3
Volumen de la probeta - con espacios vacíos (Vcv).....((π x D^2) x h)/4	1770.68 cm3	1780.13 cm3	1783.10 cm3
Porcentaje de vacíos ((Vt-Vc) x 100)/Vt	23.76 %	23.04 %	25.13 %
PROMEDIO DE % DE VACÍOS	**23.98 %**		

Fuente: Adaptado de Flores & Pacompia (2015)

4.5. Permeabilidad del concreto permeable.

Para realizar esta prueba se utilizó un permeámetro basado en la recomendación de la norma ACI 522R-10, se llena de agua el extremo superior y se mide el tiempo que demora en pasar de un lado de la probeta al otro, teniendo cuidado en los lados de la probeta para que no filtre el agua por esos extremos, antes de introducir la probeta se corta un extremo para quitar el extremo. Luego mediante la fórmula de la Ley de Darcy se calcula el coeficiente de permeabilidad.

$$k = \frac{L}{t} x \frac{a}{A} x \; ln \frac{h_1}{h_2}$$

Dónde:

K : Coef. - permeabilidad (cm/s).
L : Longitud muestra (cm).
A : Área muestra (cm2).
a : Área tubería de carga (cm2).
t : Tiempo en pasar de h1 a h2 (s).

h1 : Altura de columna de agua desde el nivel de referencia (cm).
h2 : Altura tubería de salida de agua con referencia al nivel de referencia (1cm).

Se tomo 3 probetas como muestra para el ensayo de permeabilidad:

Tabla 18: Resultados de ensayo permeabilidad.

PROBETA		M1-CP-28	M2-CP-28	M3-CP-28
t	(s)	62.15	58.15	64.58
a	(cm2)	95.03	95.03	95.03
A	(cm2)	81.77	80.92	81.68
L	(cm)	15.14	15.23	15.05
h1	(cm)	29.98	30.05	29.97
h2	(cm)	1.00	1.00	1.00
K	(cm/s)	0.963	1.047	0.922
K medio	(cm/s)	0.977		
Desviación Estándar		0.06		

Fuente: E. Propia

El factor de permeabilidad calculado esta entre el intervalo de 0.14 a 1.22 cm/s, en nuestro caso se tiene 0.977 cm/s el cual está dentro del intervalo para concreto permeable, siendo este valor adecuado para una intensidad de lluvia de 20.3 mm/hr. puesto que se encuentra cercano al valor máximo de 1.22 cm/s.

Se tiene una desviación estándar de 0.06 que nos indica que la dispersión es muy baja respecto a su media, por lo que el resultado promedio de las 3 muestras es fiable, López (Desviación estándar o típica, 2017, párr.1).

4.6. Intensidad de precipitaciones

De acuerdo al módulo de estimación de curvas de Intensidad, duración y frecuencia de Senamhi (Modulo IDF, 2021) se tiene el escenario histórico según la siguiente tabla:

Intensidades de precipitación, para diferentes periodos de retorno y duraciones.

Duración	**TR2**	**TR5**	**TR10**	**TR30**
1-hr	**16.1**(15.1-17.6)	**18.4**(17.2-20.1)	**20.3**(18.9-22.3)	**23.8**(22.1-26.1)
2-hr	**10.3**(9.7-11.2)	**11.8**(11.0-12.9)	**13.0**(12.1-14.3)	**15.2**(14.1-16.7)
3-hr	**8.0**(7.5-8.7)	**9.1**(8.5-9.9)	**10.0**(9.3-11.0)	**11.7**(10.9-12.9)
4-hr	**6.6**(6.2-7.2)	**7.5**(7.1-8.2)	**8.3**(7.8-9.1)	**9.8**(9.0-10.7)
5-hr	**5.7**(5.4-6.2)	**6.5**(6.1-7.1)	**7.2**(6.7-7.9)	**8.4**(7.8-9.3)
6-hr	**5.1**(4.8-5.6)	**5.8**(5.4-6.4)	**6.4**(6.0-7.0)	**7.5**(7.0-8.3)
7-hr	**4.6**(4.3-5.0)	**5.3**(4.9-5.8)	**5.8**(5.4-6.4)	**6.8**(6.3-7.5)
8-hr	**4.2**(4.0-4.6)	**4.8**(4.5-5.3)	**5.3**(5.0-5.8)	**6.2**(5.8-6.9)
9-hr	**3.9**(3.7-4.3)	**4.5**(4.2-4.9)	**4.9**(4.6-5.4)	**5.8**(5.4-6.4)
10-hr	**3.7**(3.4-4.0)	**4.2**(3.9-4.6)	**4.6**(4.3-5.1)	**5.4**(5.0-6.0)
11-hr	**3.5**(3.2-3.8)	**3.9**(3.7-4.3)	**4.3**(4.1-4.8)	**5.1**(4.7-5.6)
12-hr	**3.3**(3.1-3.6)	**3.7**(3.5-4.1)	**4.1**(3.8-4.5)	**4.8**(4.5-5.3)
13-hr	**3.1**(2.9-3.4)	**3.5**(3.3-3.9)	**3.9**(3.6-4.3)	**4.6**(4.2-5.0)
14-hr	**3.0**(2.8-3.2)	**3.4**(3.2-3.7)	**3.7**(3.5-4.1)	**4.4**(4.0-4.8)
15-hr	**2.8**(2.7-3.1)	**3.2**(3.0-3.5)	**3.6**(3.3-3.9)	**4.2**(3.9-4.6)
16-hr	**2.7**(2.5-3.0)	**3.1**(2.9-3.4)	**3.4**(3.2-3.7)	**4.0**(3.7-4.4)
17-hr	**2.6**(2.5-2.8)	**3.0**(2.8-3.3)	**3.3**(3.1-3.6)	**3.8**(3.6-4.2)
18-hr	**2.5**(2.4-2.7)	**2.9**(2.7-3.1)	**3.2**(3.0-3.5)	**3.7**(3.4-4.1)
19-hr	**2.4**(2.3-2.6)	**2.8**(2.6-3.0)	**3.1**(2.9-3.4)	**3.6**(3.3-3.9)
20-hr	**2.4**(2.2-2.6)	**2.7**(2.5-2.9)	**3.0**(2.8-3.2)	**3.5**(3.2-3.8)
21-hr	**2.3**(2.1-2.5)	**2.6**(2.4-2.8)	**2.9**(2.7-3.1)	**3.4**(3.1-3.7)
22-hr	**2.2**(2.1-2.4)	**2.5**(2.4-2.8)	**2.8**(2.6-3.1)	**3.3**(3.0-3.6)
23-hr	**2.1**(2.0-2.3)	**2.5**(2.3-2.7)	**2.7**(2.5-3.0)	**3.2**(2.9-3.5)
24-hr	**2.1**(2.0-2.3)	**2.4**(2.2-2.6)	**2.6**(2.5-2.9)	**3.1**(2.9-3.4)

Para un periodo de retorno de 10 años con una duración de 1 hora se tiene un intervalo de 18.9 a 22.3 mm/hr, el diseño escogido para el concreto permeable es de 20.3 mm/hr por lo cual, está dentro del rango establecido para la intensidad de precipitación del diseño del concreto permeable.

4.7. Capacidad del sistema de drenaje de aguas pluviales.

Tomando como referencia el Expediente de Drenaje Pluvial de la ciudad de Juliaca, en el ítem de Calculo Hidrológico e Hidráulico, se definió que el diseño fue realizado para el Drenaje Mayor para un periodo de retorno de 25 años y el Drenaje Menor para un periodo de retorno de 10 años con precipitaciones máximas de 46.80 mm en 24 horas según datos de la estación climatológica de Juliaca, referenciados en anexos (datos del expediente técnico del drenaje pluvial de la ciudad de Juliaca) del trabajo de investigación de Rojas y Humpiri (2016, p. 238). Para el mismo periodo máximo de 24 horas tenemos 2.6 mm/hr según Senamhi (2021) con una permeabilidad de 0.977 cm/s de infiltración, por lo que la capacidad de diseño es inferior al del Drenaje Menor Pluvial de la ciudad de Juliaca.

4.8. Análisis Estadístico

Método estadístico utilizado: t-student

Hipótesis general: La adición de plastificante al diseño de mezcla del concreto permeable aumentará la resistencia a la compresión como alternativa para el drenaje pluvial en Juliaca 2021.

TEMA DE TESIS	HIPÓTESIS A COMPROBAR	PRUEBA ESTADÍSTICA	DECISIÓN
Diseño de concreto permeable con adición de plastificante para mejorar la resistencia a la compresión como alternativa para el drenaje pluvial en Juliaca 2021	Ho: No hay diferencia entre los dos grupos de muestra con y sin plastificante	t Student: para dos grupos	Si la significancia es mayor o igual a 0.05, se acepta la hipótesis nula
	H1: Si hay diferencia entre los dos grupos de muestra con y sin plastificante	t Student: para dos grupos	Si la significancia es menor o igual a 0.05, se acepta la hipótesis alternativa

Resistencia a la Compresión a los 7 días

Tabla 19: Resistencia a la compresión a los 7 días – Análisis Estadístico.

ID	TIPO	f'c (kg/cm2)	f'c promedio (kg/cm^2)
M1-SP-07	Diseño Patrón	89.14	89.92
M2-SP-07	Diseño Patrón	90.70	
M3-SP-07	Diseño Patrón	91.12	88.39
M4-SP-07	Diseño Patrón	83.85	
M5-SP-07	Diseño Patrón	90.19	
M1-CP-07	**Con Plastificante**	**97.65**	**95.88**
M2-CP-07	**Con Plastificante**	**94.10**	
M3-CP-07	**Con Plastificante**	**96.91**	**93.30**
M4-CP-07	**Con Plastificante**	**87.35**	
M5-CP-07	**Con Plastificante**	**95.65**	

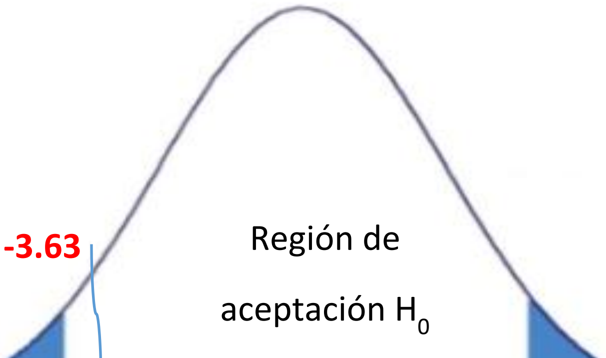
Fuente: E. Propia

Tabla 20: Variables - Análisis Estadístico – para 7 días.

	1	**2**
	Diseño patrón	**Con Plastificante**
Promedio	89.15 kg/cm^2	94.59 kg/cm^2
Varianza	1.18	3.31
Varianza Común	2.241145	
n	2	2
t	3.63	
GL	2	
Alfa	0.05	
Valor critico:	4.30	
P valor:	0.0681811	

Fuente: E. Propia

Figura 16: Distribución Normal a los 7 días (Campana de Gauss con dos colas)



Fuente: E. Propia

En relación al promedio de la resistencia a la compresión a los 7 días, se tiene un incremento en la resistencia de 5.75% en relación al diseño patrón y se tiene una varianza de Pvalor de 0.0681811 el cual es mayor a 0.05, con lo cual a los 7 días no hay diferencia entre los dos grupos por lo que se acepta ho.

Resistencia a la Compresión a los 14 días

Tabla 21: Resistencia a la compresión a los 14 días – Análisis Estadístico.

ID	TIPO	f'c (kg/cm2)	f'c promedio (kg/cm^2)
M1-SP-14	Diseño Patrón	131.64	130.75
M2-SP-14	Diseño Patrón	129.86	
M3-SP-14	Diseño Patrón	118.04	129.00
M4-SP-14	Diseño Patrón	135.36	
M5-SP-14	Diseño Patrón	133.61	
M1-CP-14	**Con Plastificante**	**138.76**	**142.54**
M2-CP-14	**Con Plastificante**	**146.32**	
M3-CP-14	**Con Plastificante**	**131.25**	**136.46**
M4-CP-14	**Con Plastificante**	**141.26**	
M5-CP-14	**Con Plastificante**	**136.88**	

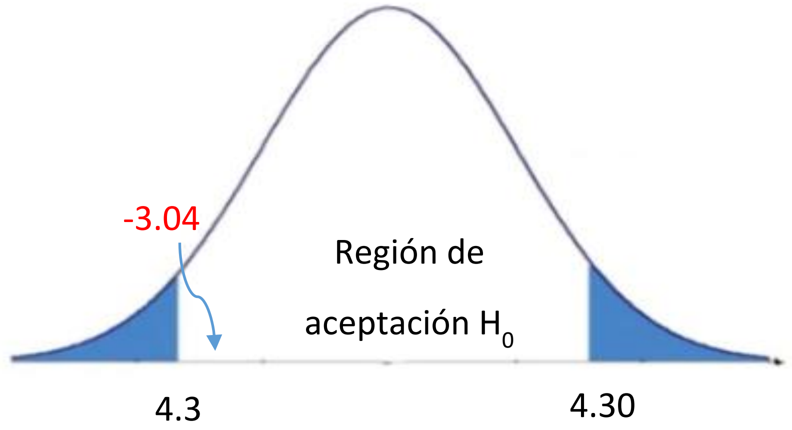
Fuente: E. Propia

Tabla 22: Variables - Análisis Estadístico – para 14 días.

	1	2
	Diseño patrón	**Con Plastificante**
Promedio	129.88 kg/cm^2	139.50 kg/cm^2
Varianza	1.53	18.46
Varianza Común	9.994181	
n	2	2
t	3.04	
GL	2	
Alfa	0.05	
Valor critico:	4.30	
P valor:	0.0930661	

Fuente: E. Propia

Figura 17: Distribución Normal a los 14 días (Campana de Gauss con dos colas)



Fuente: E. Propia

En relación al promedio de la resistencia a la compresión a los 14 días, se tiene un incremento en la resistencia de 6.90% en relación al diseño patrón y se tiene una varianza de Pvalor de 0.0930661 el cual es mayor a 0.05, con lo cual a los 14 días no hay diferencia entre los dos grupos por lo que se acepta ho.

Resistencia a la Compresión a los 28 días

Tabla 23: Resistencia a la compresión a los 28 días – Análisis Estadístico.

ID	TIPO	f'c (kg/cm2)	f'c promedio (kg/cm^2)
M1-SP-28	Diseño patrón	158.28	162.55
M2-SP-28	Diseño patrón	166.82	
M3-SP-28	Diseño patrón	161.97	159.71
M4-SP-28	Diseño patrón	165.62	
M5-SP-28	Diseño patrón	151.54	
M1-CP-28	**Con Plastificante**	**169.76**	**171.32**
M2-CP-28	**Con Plastificante**	**172.88**	
M3-CP-28	**Con Plastificante**	**167.84**	**166.91**
M4-CP-28	**Con Plastificante**	**161.75**	
M5-CP-28	**Con Plastificante**	**171.13**	

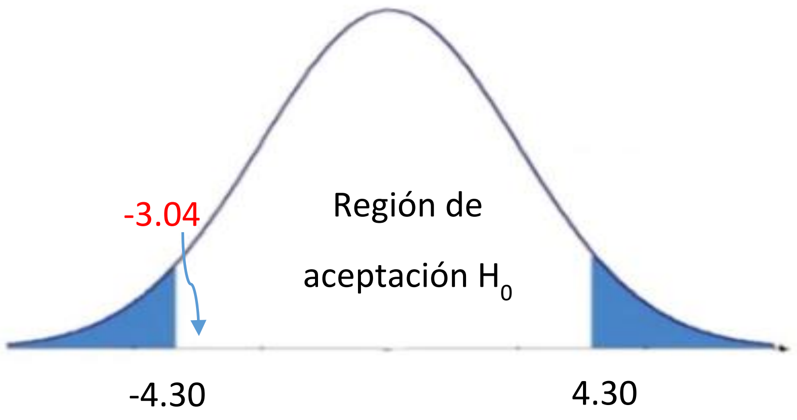
Fuente: E. Propia

Tabla 24: Variables - Análisis Estadístico – para 28 días.

	1	**2**
	Diseño patrón	**Con Plastificante**
Promedio	161.13 kg/cm^2	169.11 kg/cm^2
Varianza	4.03	9.74
Varianza Común	6.885778	
n	2	2
t	3.04	
GL	2	
Alfa	0.05	
Valor critico:	4.30	
P valor:	0.0931845	

Fuente: E. Propia

Figura 18: Distribución Normal a los 28 días (Campana de Gauss con dos colas)



Fuente: E. Propia

En relación al promedio de la resistencia a la compresión a los 28 días, se tiene un incremento en la resistencia de 4.72% en relación al diseño patrón y se tiene una varianza de Pvalor de 0.0931845 el cual es mayor a 0.05, con lo cual a los 28 días no hay diferencia entre los dos grupos por lo que se acepta ho.

Por lo que se concluye que el concreto permeable con la incorporación de plastificante al 5% del peso del cemento y con un 10% de agregado fino realizando la prueba T Student determina que no existe una diferencia significativa entre los dos grupos, a pesar que se tiene un aumento en la resistencia a la compresión a los 7, 14 y 28 días, esta no es significativa; por lo que se acepta la hipótesis nula (ho).

V. DISCUSIÓN

Flores y Pacompia (2015, p. 235), se proponen conseguir un diseño de mezcla de concreto permeable para pavimentos que alcance los 175 kg/cm2 adicionando tiras de polipropileno para incrementar la resistencia pero esta no es significativa, a medida que se va incrementando el porcentaje de Tiras presenta una reducción de su contenido de vacíos y permeabilidad, se utilizaron dos tipos de agregado grueso del Huso Nº 8 caracterizado por material de ½” (12.5mm) y 3/8” (9.5mm) y del Huso Nº 57 caracterizado por material de 1” (25mm), llegando a la conclusión que el concreto elaborado con el agregado del Huso Nº 57 es menor a la del Huso Nº 08 en un 26.13%.

En relación al estudio de Flores y Pacompia (2015, p. 235), en nuestro caso trabajamos con material seleccionado de 3/8” y con un 10% de agregado fino por lo que obtuvimos resistencias medias, obteniendo un máximo de 171.32 kg/cm2 y un promedio de 169.11 kg/cm2 a los 28 días.

Jacinto (2021, p. 194), a través del uso de diferentes cantidades de agregado fino y el uso de aditivo plastificante, determinó las propiedades mecánicas del concreto permeable. Se determino que cuando se utiliza porcentajes de 15 % y 20 % de agregado fino en combinación con el plastificante se obtiene incrementos en la resistencia a compresión de un 11%, la misma correlación que propone el ACI 522-R que determina resistencias a compresión superiores a los 120 kg/cm2, cuando se emplea de 10% en adelante de agregado, utilizando el 10% de agregado en adelante se tiene un asentamiento diferente a 0 cm.

Teniendo como referencia el trabajo de investigación de Jacinto (2021, p. 194) podemos determinar que no pudimos alcanzar resistencias mayores debido a que trabajamos con 10% de agregado fino y material seleccionado de 3/8” y no con proporciones de material retenido para el huso Nº 08 que era el que correspondía para este tamaño de material.

En su proyecto de investigación Arteaga y Patiño (2018, p. 89), logran un diseño de mezcla con 18% de vacíos, llegando a conseguir una resistencia a la compresión de 195 kg/cm2 y una permeabilidad de 7.99 mm/min a los 28 días, se realizó varios ensayos con contenido de vacíos de 14%, 18%, 20% y 23%, llegando a su máxima resistencia con un contenido de vacíos de 18% y a medida que se incrementaba el contenido de vacíos a 20% y 23% la resistencia disminuyo, también se determinó que a medida que se incrementaba el contenido de vacíos, disminuía la proporción del aditivo SikaCem desde 5.16 kg/m3 con 14% de vacíos a 2.95 kg/m3 para 23% de vacíos.

En comparación con el estudio de Arteaga y Patiño (2018, p. 89), se obtuvo un contenido de vacíos del 23.98% debido a que se utilizó agregado grueso de 3/8” seleccionado, por lo cual se obtuvo una resistencia media a la compresión en relación al mismo estudio. En nuestra investigación al haber alcanzado una resistencia menor al de Arteaga y Patiño se ha visto afectada nuestra resistencia por una mayor cantidad de vacíos.

El desempeño del plastificante y superplastificantes según las indicaciones y brochures de Sika (2020, p. 10) indican que reduce la cantidad de agua en el caso de los plastificantes en hasta un 20% y en el caso de los superplastificantes hasta en un 40% estos porcentajes se dan para mezclas convencionales donde predomina el agregado fino, el material que predomina para estos porcentajes es el agregado fino que pasa por el tamiz de 3/8” y los retenidos en las mallas Nº 4, Nº 8, Nº 16, Nº 50, Nº 100 y Nº 200. Teniendo relaciones de agua/cemento entre 0.25 a 0.40.

En nuestro caso no pudimos obtener un desempeño optimo en relación al uso de plastificante en relación a la disminución de la relación a/c debido a que se trabajó con un 10% de agregado fino y con un material seleccionado de 3/8”.

VI. CONCLUSIONES

Conclusión general

Se obtuvo el diseño de concreto permeable con adición de plastificante el cual mejoro la resistencia en un porcentaje mínimo con relación al diseño patrón sin plastificante, el diseño con un contenido de vacíos en estado endurecido del 23.98 % y con un coeficiente de infiltración del 0.977 cm/s, logro una resistencia adicional del 5.75% a los 7 días, de 6.90% a los 14 días y de 4.72% a los 28 días en relación al diseño patrón sin plastificante, por lo cual se llega a concluir que si bien se logró obtener un porcentaje adicional de resistencia esta aun no es el adecuado para su aplicación, debido a que el plastificante si bien es un reductor de agua para las mezclas de concreto este no es significativo en mezclas que contengan agregados gruesos como es el caso del concreto permeable, en donde mejor desempeño se consigue es cuando la mezcla contiene agregado fino en un 90% del porcentaje de mezcla hasta un 20% de reducción de agua, debido a que el plastificante funciona como un distribuidor del agua dentro de la mezcla.

El uso de aditivo plastificante incrementa la resistencia a la compresión, pero se tiene un P-valor mayor en relación al límite Alfa de nuestros resultados según la prueba estadística T-Student, donde el P-valor es mayor al límite de 0.05 de significancia, por lo que hay que seguir evaluando otros porcentajes tanto de aditivo y agregados para lograr una mayor resistencia y ser aplicable en el sistema de drenaje pluvial de la ciudad.

Conclusiones específicas

- Se logro determinar que las características físico- mecánicas del agregado a ser utilizado en la dosificación del concreto permeable son competentes, a través de los diferentes ensayos de laboratorio realizados.

- La resistencia promedio a la compresión obtenido a los 7 días sin plastificante fue de 89.15 kg/cm2 y con plastificante de 94.59 kg/cm2 obteniendo un incremento de 5.75% en la resistencia, y un valor de significancia de 0.068 > 0.05, el cual nos indica que está encima del límite; la resistencia promedio a la compresión obtenido a los 14 días sin plastificante fue de 129.88 kg/cm2 y con plastificante de 139.50 kg/cm2 obteniendo un incremento de 6.90% en la resistencia, y un valor de significancia de 0.093 > 0.05, el cual nos indica que está encima del límite y la resistencia promedio a la compresión obtenido a los 28 días sin plastificante fue de 161.13 kg/cm2 y con plastificante de 169.11 kg/cm2 obteniendo un incremento de 4.72% en la resistencia y un valor de significancia estadística de 0.093 > 0.05, el cual nos indica que está encima del límite.

- El contenido de vacíos o porosidad alcanzado mediante la determinación de la densidad del concreto fue de 23.98% el cual está en el rango recomendado por ACI-522R (2010, p. 2).

- La permeabilidad del concreto fue de 0.977 cm/s el cual está dentro del parámetro recomendado por ACI-522R (2010, p. 11), este se determinó mediante la ley de Darcy.

- La intensidad de la precipitación para un periodo de retorno de 10 años y una hora de duración del diseño del concreto fue de 20.3 mm/hr, el cual está dentro del rango determinado por la tabla de Intensidad, duración y frecuencia de la tabla IDF de Senamhi para la ciudad de Juliaca.

- La capacidad del sistema de drenaje de aguas pluviales del Drenaje Menor para el sistema de Drenaje Pluvial para la ciudad de Juliaca es de 46.80 mm en 24 horas por lo que será suficiente para el mismo periodo de 24 horas y un periodo de retorno de 10 años del IDF de la ciudad de Juliaca el cual tiene una intensidad de 2.6 mm.

VII. RECOMENDACIONES

Para lograr un concreto permeable con resistencias mayores al promedio es necesario buscar la combinación optima de todos los materiales, puesto que al contener vacíos esta se debilita, es por ello que es necesario encontrar ese equilibrio entre la permeabilidad y resistencia a la compresión es por ello que se recomienda utilizar diferentes porcentajes de plastificante y agregado fino para conseguir un concreto más resistente.

- Se recomienda realizar estudios para probar diferentes tamaños de agregados para ver cuál es el más resistente y a la vez el que mejor se adapte para conseguir un concreto resistente al tráfico de vehículos pesados y así poder aplicarlo en vías urbanas.

- Para la rotura de las probetas de concreto, se recomienda el recapeado de probetas con el método de capping con lo cual se consigue que la distribución de cargas sea uniforme y así evitar que las probetas se rompan por fallas en los extremos, además de realizar mayor cantidad de probetas de concreto para tener una distribución estadística más fiable mediante la medición adecuada de la dispersión en relación a la media con mayor cantidad de datos.

- El contenido de vacíos está relacionado con la permeabilidad del concreto por lo que se recomienda que se realice más pruebas para ver la relación correcta entre el contenido de vacíos y permeabilidad que permita obtener un mejor desempeño del concreto.

- En relación a la permeabilidad se recomienda la revisión de las intensidades de lluvia para la cual se va diseñar para periodos máximos de lluvia.

- Se recomienda trabajar con diferentes métodos para realizar el análisis de frecuencia de datos, puesto que muchas veces las estaciones meteorológicas tienen interrupciones en la medición de sus datos meteorológicos.

- Evaluar la situación actual del drenaje de la ciudad de Juliaca para tener mayores criterios de diseño como las pendientes por zonas, contaminación de residuos sólidos que afectan los sistemas de drenaje.

.

REFERENCIAS

- ARTEAGA Alvarez, Deicy M. y PATIÑO Cifuentes, Cesar A. (2018). Análisis de contenidos de vacíos para el diseño de mezclas del concreto permeable con aditivo SikaCem en pavimentos Lima, 2018. Tesis (Ingeniero Civil). Lima: Universidad Cesar Vallejo, 2018.

- RONDOY Aguilar, Rosana N. (2019). Diseño de un Pavimento Permeable y Drenaje Pluvial del Tramo Jr. San Lorenzo – Mercado de Piura, 2018. Tesis (Ingeniero Civil). Piura: Universidad Cesar Vallejo, 2019.

- FLORES Quispe, Cesar E. y PACOMPIA Calcina, Ivan A. (2015). Diseño de mezcla de concreto permeable con adición de tiras de plástico para pavimentos f’c 175 kg/cm2 en la ciudad de Puno. Tesis (Ingeniero Civil). Puno: Universidad Nacional del Altiplano, 2015.

- RODRÍGUEZ Hernández, J. (2008). Estudio, análisis y diseño de secciones permeables de firmes para vías urbanas con un comportamiento adecuado frente a la colmatación y con capacidad portante necesaria para soportar tráficos ligeros. Tesis (Doctor en Ingeniería Civil). Santander. Universidad de Cantabria, 2008.

- JACINTO Aquino, J.E. (2021). Diseño de mezcla de concreto permeable utilizando diferentes porcentajes de agregado fino y aditivos en la ciudad de Chiclayo. Tesis (Ingeniero Civil). Chiclayo: Universidad Católica Santo Toribio de Mogrovejo, 2021.

- FELIPE, Moujir y CASTAÑEDA (2014). Diseño y Aplicación de Concreto Poroso para Pavimentos. Tesis (Ingeniero Civil). Cali, Pontificia Universidad Javeriana, 2014.

- ARTEAGA y PATIÑO (2018). Análisis de contenidos de vacíos para el diseño de mezclas del concreto permeable con aditivo SikaCem en pavimentos Lima,

2018. Tesis (Ingeniero Civil). Lima, Universidad Cesar Vallejo, 2018.

- JACINTO Aquino (2021). Diseño de Mezcla de Concreto Permeable utilizando diferentes porcentajes de agregado fino y aditivos en la ciudad de Chiclayo. Tesis (Ingeniero Civil). Chiclayo, Universidad Católica Santo Toribio de Mogrovejo, 2021.

- RODRÍGUEZ, A. S. (2015). Guía para el Diseño y Construcción de Pavimentos Rígidos. Mexico D.F.: Instituto Mexicano del Cemento y Concreto.

- MONTEJO Fonseca, A. (2006), Ingeniería de Pavimentos, Fundamentos, estudios básicos y diseño, Colombia, Universidad Católica de Colombia.

- Instituto de Ingeniería UNAM (1997), Manual de Tecnología del Concreto, México D.F, Editorial Limusa S.A.

- PASQUEL Carbajal, E. (1998), Tópicos de Tecnología del Concreto en el Perú, Lima, Editorial Colegio de Ingenieros del Perú.

- Watanabe, S. (2005). Study on storm water control by permeable pavement and infiltration pipes. Water Science Technology.

- TENNIS, P. D., LEMING M. L. y AKERS D. J. (2004). Pervious concrete paviments. Portland Cement Association. Disponible en http://myscmap.sc.gov/marine/NERR/pdf/PerviousConcrete_pavements.pdf

- KATHRYN Schaus. L (2007), Tesis para Master en Ciencias: Porous Asphalt Pavement Designs: Proactive Desing for Cold Climate Use, University of Waterloo, Ontario Canada).

- BRUCE K, Ferguson (2005). Porous Pavements, Taylor & Francis Group, Boca Raton, Florida.

- SHU Wei Goh, y ZHANPING You (2012). Mechanical Properties of Porous Asphalt Pavement Materials with Warm Mix Asphalt and RAP, journal of transportation engineering, January 2012.

- GONZÁLEZ Chávez, J. P. y ROCA Torres, R (2003), Influencia de la forma, granulometría y textura superficial del agregado grueso en las propiedades del concreto fresco y endurecido, Arequipa. Tesis (Ingeniero Civil). Universidad Nacional de San Agustín, 2003.

- AIRE Untiveros, Carlos (2010), Hormigón permeable: consideraciones para el diseño de mezclas, diseño del espesor de pavimento y métodos de prueba, México D.F, Revista Técnica Cemento Hormigón nº 941, nov-dic 2010.

- GERSSON F. B. Sandoval, ISAAC Galobardes, NICOLE Schwantes-Cezario, ANDRÉ Campos, BERENICE M.Toralles (2019), Correlation between permeability and porosity for pervious concrete, [online]. Disponible en https://dialnet.unirioja.es/servlet/articulo?codigo=7029918.

- ULLOA-Mayorga Vivian A., URIBE-Garcés Manuel A., PAZ-Gómez Diego P., ALVARADO Yezid A., TORRES Benjamín, and GASCH Isabel (2018), Performance of pervious concrete containing combined recycled aggregates. Engineering and Research vol. 38 Nº 2. [online]. Disponible en https://dialnet.unirioja.es/servlet/articulo?codigo=6629777.

- BATEZINI, Rafael; BALBO, José Tadeu; HASELBACH, Liv; CURVO, Filipe de Oliveira; KALLEDER, Guilherme Nunes; SATO, Beatriz Sayuri; ZEMA, Domênico. (2021). Experimental appraisal for characterizing laboratorial and field performance parameters of pervious concrete pavement. [online]. Disponible en https://www.scielo.br/j/ac/a/PkcmqRYqkzkDyDXkzYV6Ygx/?lang=en.

- COSTA, F. B. P.; LORENZI, A.; HASELBACH, L.; SILVA Filho, L. C. P. (2018). Best practices for pervious concrete mix design and laboratory tests. Ibracon

Structures and Materials Journal. [online]. Disponible en https://www.scielo.br/j/riem/a/tXhWYPYvKTgJxXH5vbFvQsQ/?lang=en.

- XUDONG Chen, DANDAN Shi, NAN Shen, SHENGTAO Li and SAISAI Liu (2019), Experimental Study and Analytical Modeling on Fatigue Properties of Pervious Concrete Made with Natural and Recycled Aggregates. Disponible en https://ijcsm.springeropen.com/articles/10.1186/s40069-018-0305-0.

- MOHAMMED Sonebia, MOHAMED Bassuonib, AMMAR Yahiac (2016), Pervious Concrete: Mix Design, Properties and Applications. Publicado en ResearchGate. Disponible en : https://www.researchgate.net/publication/311971713_Pervious_Concrete_Mix_Design_Properties_and_Applications

- F. B. P. COSTAA. LORENZIL. HASELBACHL. C. P. SILVA FILHO (2018), Best practices for pervious concrete mix design and laboratory tests, Publicado en Scielo Brasil. Disponible en: https://www.scielo.br/j/riem/a/tXhWYPYvKTgJxXH5vbFvQsQ/?lang=en.

- PIERALISI Ricardo (2016), Characterization and modelling of pervious concrete. Barcelona, Universitat Politècnica de Catalunya.

- PÉREZ Carmona Rafael (2015). Diseño y Construcción de Alcantarillados Sanitario Pluvial y Drenaje de Carreteras. Ecoc Ediciones, Bogotá.

- SAMPIERI Roberto (2014), Metodología de la Investigación. 6ta edición. Mc Graw – Hill / Interamericana Editores, S.A. de C.V.

- CEMEX.COM.PE (2019). Articulo: ¿Por qué se determina la resistencia a la compresión en el concreto? [en línea]. [fecha de consulta: 27 de diciembre de 2021]. Disponible en: https://www.cemex.com.pe/-/-por-que-se-determina-la-resistencia-a-la-compresion-en-el-concreto-.

- SENAMHI (2021). Portal web del Servicio Nacional de Meteorología e Hidrología del Perú, Disponible en: ttps://www.senamhi.gob.pe/?p=pronostico-meteorologico.

- ACI-522R (2010). Report on Pervious Concrete, American Concrete Institute.

- ACI 211.3R-97 (1998). Guide for selecting proportions for no-slump concrete, American Concrete Institute.

- ASTM C33/C33M (2018). Standard Specification for Concrete Aggregates, American Society for Testing and Materials.

- Guía Normas APA, 7ma. Edición, American Psychological Association, 2020. Disponible en: https://normas-apa.org/wp-content/uploads/Guia-Normas-APA-7ma-edicion.pdf

- ROJAS Naira, Paolo C. y HUMPIRI Pari, Vladimir H. (2016). Evaluación, diseño y modelamiento del sistema de drenaje pluvial de la ciudad de Juliaca con la aplicación del software SWMM. Tesis (Ingeniero Civil). Puno: Universidad Nacional del Altiplano, 2016.

- LÓPEZ, José Francisco, Desviación estándar o típica, Diccionario Económico [en línea] subido el 02 de octubre del 2017, [fecha de consulta: 24 de febrero de 2022]. Disponible en: https://economipedia.com/definiciones/desviacion-tipica.html

ANEXOS

ANEXO 1. PANEL FOTOGRÁFICO

Figura 01: Ubicación de la cantera Isla, Juliaca.

Fuente: Google Earth

Figura 02: Recogiendo muestras de agregados de la Cantera Isla.

Fuente: Elaboración propia

Figura 03: Transportando muestras de agregados de la Cantera Isla.

Fuente: Elaboración propia

Figura 04: Realizando la selección de material grueso para los ensayos.

Fuente: Elaboración propia

Figura 05: Realizando el tamizado de material fino para el ensayo.

Fuente: Elaboración propia

Figura 06: Realizando la selección de material grueso para los ensayos.

Fuente: Elaboración propia

Figura 07: Realizando el tamizado de material fino para el ensayo.

Fuente: Elaboración propia

Figura 08: Seleccionando material de 3/8” para realizar los ensayos.

Fuente: Elaboración propia

Figura 09: Zarandeando agregado grueso por la malla de ½” para recolectar material de 3/8”.

Fuente: Elaboración propia

Figura 10: Zarandeando agregado grueso por la malla de 3/8” para retenerlo, previamente paso por la malla ½” para eliminar material mayor a esta medida.

Fuente: Elaboración propia

Figura 11: Material de 3/8” retenido en la malla.

Fuente: Elaboración propia

Figura 12: Material de 3/8” acumulado.

Fuente: Elaboración propia

Figura 14: Acumulando material de 3/8” en sacos para realizar las probetas.

Fuente: Elaboración propia

Figura 15: Transportando material acumulado.

Fuente: Elaboración propia

Figura 16: Material fino sobrante después del zarandeo.

Fuente: Elaboración propia

Figura 17: Realizando el pesado de cemento.

Fuente: Elaboración propia

Figura 18: Realizando el pesado de agregado grueso.

Fuente: Elaboración propia

Figura 19: Acumulando material pesado de agregado grueso.

Fuente: Elaboración propia

Figura 20: Dosificando el aditivo plastificante.

Fuente: Elaboración propia

Figura 21: Realizando la medición de cantidad de agua.

Fuente: Elaboración propia

Figura 22: Mezcladora para el batido de los materiales componentes del concreto permeable.

Fuente: Elaboración propia

Figura 23: Agregando materiales a la mezcladora.

Fuente: Elaboración propia

Figura 24: Revolviendo la mezcla después de extraerlo de la mezcladora.

Fuente: Elaboración propia

Figura 25: Realizando el varillado en 3 capas.

Fuente: Elaboración propia

Figura 26: Realizando el último varillado.

Fuente: Elaboración propia

Figura 27: Enrazado de la probeta.

Fuente: Elaboración propia

Figura 28: Muestras de probetas terminadas con adición de plastificante.

Fuente: Elaboración propia

Figura 29: Primeras muestras con/sin adición de plastificante.

Fuente: Elaboración propia

Figura 30: Vaciado de mezcla en moldes cilíndricos.

Fuente: Elaboración propia

Figura 31: Varillado de probetas.

Fuente: Elaboración propia

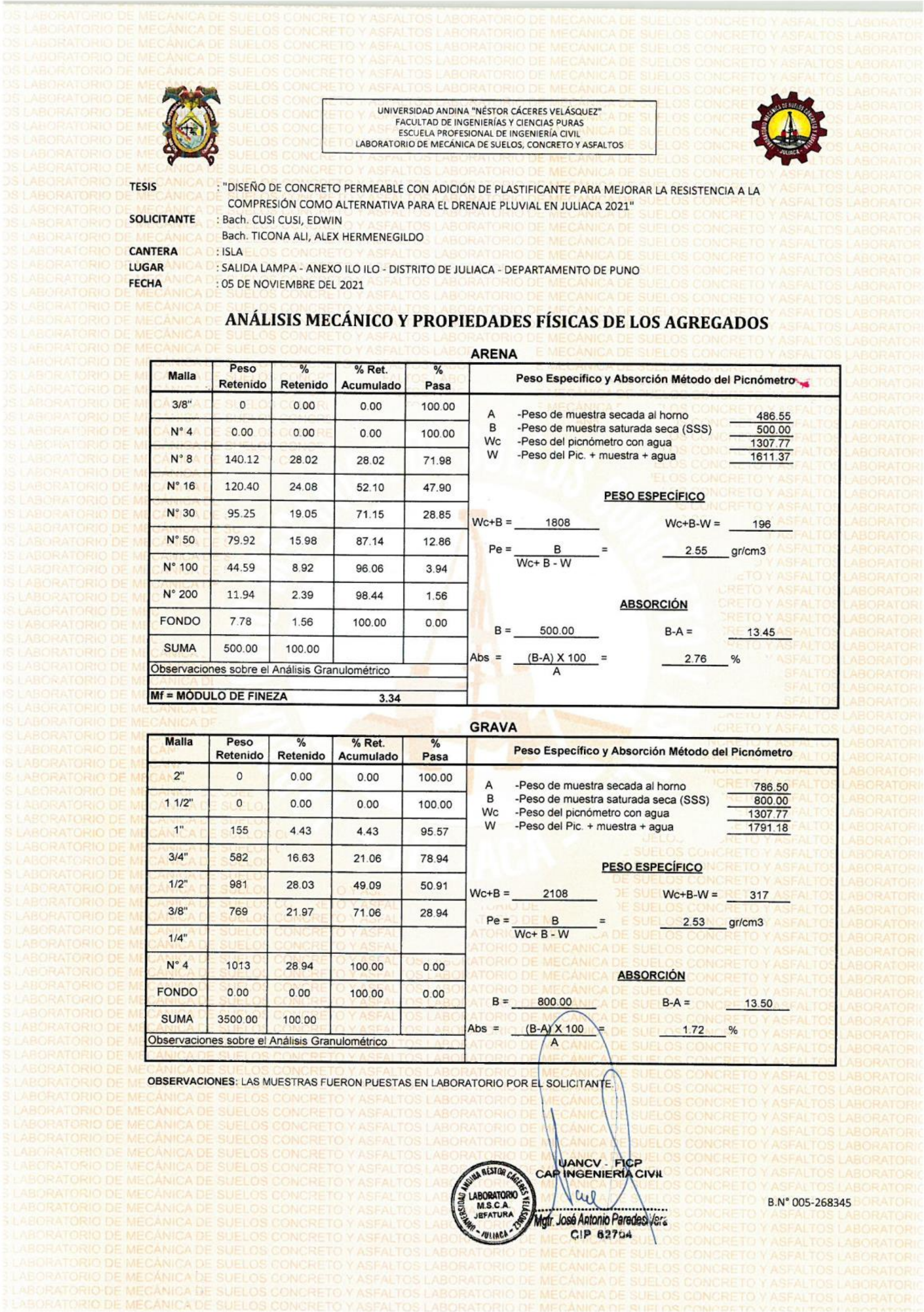
Figura 32: Desmoldando las probetas.

Fuente: Elaboración propia

Figura 33: Preparando la poza de curado.

Fuente: Elaboración propia

ANEXO 2. ENSAYOS DE LABORATORIO



UNIVERSIDAD ANDINA "NÉSTOR CÁCERES VELÁSQUEZ"
FACULTAD DE INGENIERÍAS Y CIENCIAS PURAS
ESCUELA PROFESIONAL DE INGENIERÍA CIVIL
LABORATORIO DE MECÁNICA DE SUELOS, CONCRETO Y ASFALTOS

TESIS : "DISEÑO DE CONCRETO PERMEABLE CON ADICIÓN DE PLASTIFICANTE PARA MEJORAR LA RESISTENCIA A LA COMPRESIÓN COMO ALTERNATIVA PARA EL DRENAJE PLUVIAL EN JULIACA 2021"
SOLICITANTE : Bach. CUSI CUSI, EDWIN
Bach. TICONA ALI, ALEX HERMENEGILDO
CANTERA : ISLA
LUGAR : SALIDA LAMPA - ANEXO ILO ILO - DISTRITO DE JULIACA - DEPARTAMENTO DE PUNO
FECHA : 05 DE NOVIEMBRE DEL 2021

ANÁLISIS MECÁNICO Y PROPIEDADES FÍSICAS DE LOS AGREGADOS

ARENA

Malla	Peso Retenido	% Retenido	% Ret. Acumulado	% Pasa
3/8"	0	0.00	0.00	100.00
N° 4	0.00	0.00	0.00	100.00
N° 8	140.12	28.02	28.02	71.98
N° 16	120.40	24.08	52.10	47.90
N° 30	95.25	19.05	71.15	28.85
N° 50	79.92	15.98	87.14	12.86
N° 100	44.59	8.92	96.06	3.94
N° 200	11.94	2.39	98.44	1.56
FONDO	7.78	1.56	100.00	0.00
SUMA	500.00	100.00		

Observaciones sobre el Análisis Granulométrico

Mf = MÓDULO DE FINEZA 3.34

Peso Específico y Absorción Método del Picnómetro

A	-Peso de muestra secada al horno	486.55
B	-Peso de muestra saturada seca (SSS)	500.00
Wc	-Peso del picnómetro con agua	1307.77
W	-Peso del Pic. + muestra + agua	1611.37

PESO ESPECÍFICO

Wc+B = 1808 Wc+B-W = 196

$$Pe = \frac{B}{Wc + B - W} = 2.55 \text{ gr/cm3}$$

ABSORCIÓN

B = 500.00 B-A = 13.45

$$Abs = \frac{(B-A) \times 100}{A} = 2.76 \ \%$$

GRAVA

Malla	Peso Retenido	% Retenido	% Ret. Acumulado	% Pasa
2"	0	0.00	0.00	100.00
1 1/2"	0	0.00	0.00	100.00
1"	155	4.43	4.43	95.57
3/4"	582	16.63	21.06	78.94
1/2"	981	28.03	49.09	50.91
3/8"	769	21.97	71.06	28.94
1/4"				
N° 4	1013	28.94	100.00	0.00
FONDO	0.00	0.00	100.00	0.00
SUMA	3500.00	100.00		

Observaciones sobre el Análisis Granulométrico

Peso Específico y Absorción Método del Picnómetro

A	-Peso de muestra secada al horno	786.50
B	-Peso de muestra saturada seca (SSS)	800.00
Wc	-Peso del picnómetro con agua	1307.77
W	-Peso del Pic. + muestra + agua	1791.18

PESO ESPECÍFICO

Wc+B = 2108 Wc+B-W = 317

$$Pe = \frac{B}{Wc + B - W} = 2.53 \text{ gr/cm3}$$

ABSORCIÓN

B = 800.00 B-A = 13.50

$$Abs = \frac{(B-A) \times 100}{A} = 1.72 \ \%$$

OBSERVACIONES: LAS MUESTRAS FUERON PUESTAS EN LABORATORIO POR EL SOLICITANTE.

LABORATORIO
M.S.C.A.
JEFATURA

UANCV - FICP
CAP INGENIERÍA CIVIL
Mgtr. José Antonio Paredes Vera
CIP 62704

B.N° 005-268345

UNIVERSIDAD ANDINA "NÉSTOR CÁCERES VELÁSQUEZ"
FACULTAD DE INGENIERÍAS Y CIENCIAS PURAS
ESCUELA PROFESIONAL DE INGENIERÍA CIVIL
LABORATORIO DE MECÁNICA DE SUELOS, CONCRETO Y ASFALTOS

ANÁLISIS GRANULOMÉTRICO POR TAMIZADO

NORMA: ASTM C 33

TESIS : "DISEÑO DE CONCRETO PERMEABLE CON ADICIÓN DE PLASTIFICANTE PARA MEJORAR LA RESISTENCIA A LA COMPRESIÓN COMO ALTERNATIVA PARA EL DRENAJE PLUVIAL EN JULIACA 2021"
SOLICITANTE : Bach. CUSI CUSI, EDWIN
Bach. TICONA ALI, ALEX HERMENEGILDO
CANTERA : ISLA
LUGAR : SALIDA LAMPA - ANEXO ILO ILO - DISTRITO DE JULIACA - DEPARTAMENTO DE PUNO
FECHA : 05 DE NOVIEMBRE DEL 2021

TAMICES ASTM	ABERTURA mm	PESO RETENIDO	%RETENIDO PARCIAL	%RETENIDO ACUMULADO	% QUE PASA	ESPECIF.
3"	76.200					
2 1/2"	63.500	0.00	0.00	0.00	**100.00**	
2"	50.600	0.00	0.00	0.00	**100.00**	
1 1/2"	38.100	0.00	0.00	0.00	**100.00**	
1"	25.400	155.00	4.43	4.43	**95.57**	100 %
3/4"	19.050	582.00	16.63	21.06	**78.94**	90 - 100 %
1/2"	12.700	981.00	28.03	49.09	**50.91**	
3/8"	9.525	769.00	21.97	71.06	**28.94**	20 - 55 %
1/4"	6.350					
No4	4.760	1013.00	28.94	100.00	**0.00**	0 - 10 %
BASE		0.00	0.00	0.0	100.0	
TOTAL		3500.00	100.00			
% PÉRDIDA		0.00				

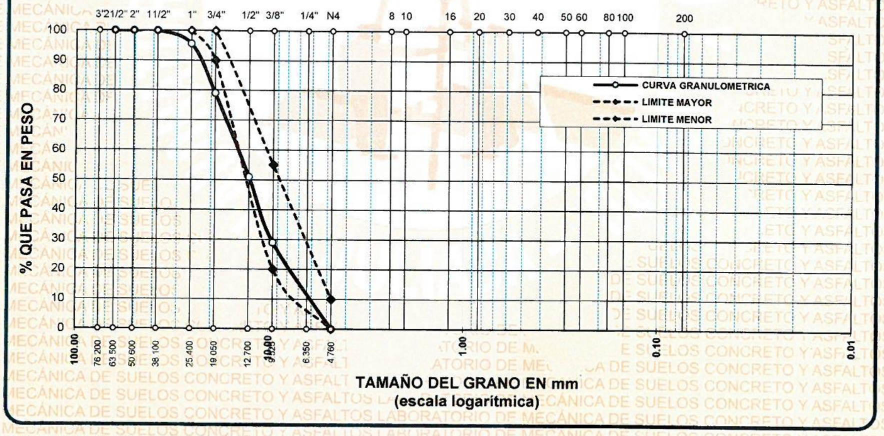
DESCRIPCIÓN DE LA MUESTRA

Peso Inicial = 3500 gr.

Tamaño máx. nominal = 3/4 "

OBSERVACIONES:

CURVA GRANULOMÉTRICA



OBSERVACIONES: LAS MUESTRAS FUERON PUESTAS EN LABORATORIO POR EL SOLICITANTE

LABORATORIO M.S.C.A. JEFATURA

UANCV - FICP
CAP INGENIERÍA CIVIL
Mgtr. José Antonio Paredes Vera
CIP 62794

B.N° 005-268345

UNIVERSIDAD ANDINA "NÉSTOR CÁCERES VELÁSQUEZ"
FACULTAD DE INGENIERÍAS Y CIENCIAS PURAS
ESCUELA PROFESIONAL DE INGENIERÍA CIVIL
LABORATORIO DE MECÁNICA DE SUELOS, CONCRETO Y ASFALTOS

ANÁLISIS GRANULOMÉTRICO POR TAMIZADO

NORMA: ASTM C 33

TESIS : "DISEÑO DE CONCRETO PERMEABLE CON ADICIÓN DE PLASTIFICANTE PARA MEJORAR LA RESISTENCIA A LA COMPRESIÓN COMO ALTERNATIVA PARA EL DRENAJE PLUVIAL EN JULIACA 2021"
SOLICITANTE : Bach. CUSI CUSI, EDWIN
Bach. TICONA ALI, ALEX HERMENEGILDO
CANTERA : ISLA
LUGAR : SALIDA LAMPA - ANEXO ILO ILO - DISTRITO DE JULIACA - DEPARTAMENTO DE PUNO
FECHA : 05 DE NOVIEMBRE DEL 2021

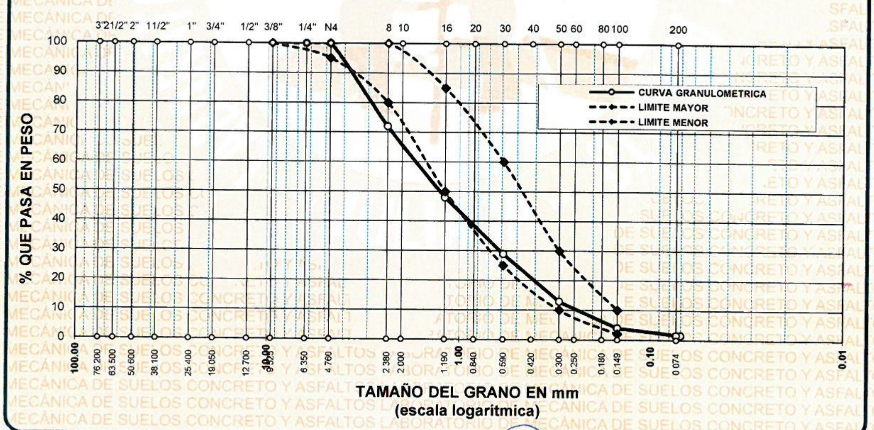
TAMICES ASTM	ABERTURA mm	PESO RETENIDO	% RETENIDO	%RET. ACUMULADO	% QUE PASA	ESPECIF.
3/8"	9.525	0.00	0.00	0.00	**100.00**	100%
1/4"	6.350	0.00	0.00	0.00	**100.00**	
No4	4.760	0.00	0.00	0.00	**100.00**	95 - 100 %
No8	2.380	140.12	28.02	28.02	**71.98**	80 - 100 %
No10	2.000					
No16	1.190	120.40	24.08	52.10	**47.90**	50 - 85 %
No20	0.840					
No30	0.590	95.25	19.05	71.15	**28.85**	25 - 60 %
No40	0.420					
No 50	0.300	79.92	15.98	87.14	**12.86**	10 - 30 %
No60	0.250					
No80	0.180					
No100	0.149	44.59	8.92	96.06	**3.94**	2-10%
No200	0.074	11.94	2.39	98.44	**1.56**	
BASE		7.78	1.56	100	**0.00**	
TOTAL		500.00	100.00			
% PERDIDA		1.56				

DESCRIPCIÓN DE LA MUESTRA

Peso Inicial = 500 **gr.**
Módulo de Fineza = **3.34**

OBSERVACIONES:

CURVA GRANULOMÉTRICA



OBSERVACIONES: LAS MUESTRAS FUERON PUESTAS EN LABORATORIO POR EL SOLICITANTE

LABORATORIO
M.S.C.A.
JEFATURA

UANCV - FICP
CAP INGENIERÍA CIVIL
Mgtr. José Antonio Paredes Vera
CIP 52794

B.N° 005-268345

UNIVERSIDAD ANDINA "NÉSTOR CÁCERES VELÁSQUEZ"
FACULTAD DE INGENIERÍAS Y CIENCIAS PURAS
ESCUELA PROFESIONAL DE INGENIERÍA CIVIL
LABORATORIO DE MECÁNICA DE SUELOS, CONCRETO Y ASFALTOS

PESOS UNITARIOS

NTP 400.017 - ASTM C - 29 AASHTO T - 19

TESIS : "DISEÑO DE CONCRETO PERMEABLE CON ADICIÓN DE PLASTIFICANTE PARA MEJORAR LA RESISTENCIA A LA COMPRESIÓN COMO ALTERNATIVA PARA EL DRENAJE PLUVIAL EN JULIACA 2021"
SOLICITANTE : Bach. CUSI CUSI, EDWIN
: Bach. TICONA ALI, ALEX HERMENEGILDO
CANTERA : ISLA
LUGAR : SALIDA LAMPA - ANEXO ILO ILO - DISTRITO DE JULIACA - DEPARTAMENTO DE PUNO
FECHA : 05 DE NOVIEMBRE DEL 2021

DENSIDAD MINIMA AGREGADO (ARENA)

PESO DEL MOLDE	**5970 gr**	**5970 gr**	**5970 gr**
VOLUMEN DEL MOLDE	**2163 cm3**	**2163 cm3**	**2163 cm3**
COLOCACION DE MUESTRA A MOLDE	**CAIDA LIBRE**	**CAIDA LIBRE**	**CAIDA LIBRE**
PESO DEL MOLDE + MUESTRA SUELTA	9415.00 gr	9385.00 gr	9405.00 gr
PESO DE LA MUESTRA SUELTA	3445.00 gr	3415.00 gr	3435.00 gr
DENSIDAD MINIMA DE LA MUESTRA SECA	**1.593 gr/cm3**	**1.579 gr/cm3**	**1.588 gr/cm3**
PROMEDIO		**1.586 gr/cm3**	

DENSIDAD MINIMA AGREGADO (ARENA)

PESO DEL MOLDE	**5970 gr**	**5970 gr**	**5970 gr**
VOLUMEN DEL MOLDE	**2163 cm3**	**2163 cm3**	**2163 cm3**
Nº DE CAPAS	**3**	**3**	**3**
Nº DE GOLPES POR CAPA	**25**	**25**	**25**
PESO DEL MOLDE + MUESTRA COMPACTADA	9520.00 gr	9565.00 gr	9495.00 gr
PESO DE LA MUESTRA COMPACTADA	3550.00 gr	3595.00 gr	3525.00 gr
DENSIDAD MAXIMA DE LA MUESTRA SECA	**1.641 gr/cm3**	**1.662 gr/cm3**	**1.630 gr/cm3**
PROMEDIO		**1.644 gr/cm3**	

OBSERVACIONES: LAS MUESTRAS FUERON PUESTAS EN LABORATORIO POR EL SOLICITANTE

LABORATORIO
M.S.C.A.
JEFATURA

UANCV - FICP
CAP INGENIERÍA CIVIL
Mgtr. José Antonio Paredes Vera
CIP 82794

B.N° 005-268345

UNIVERSIDAD ANDINA "NÉSTOR CÁCERES VELÁSQUEZ"
FACULTAD DE INGENIERÍAS Y CIENCIAS PURAS
ESCUELA PROFESIONAL DE INGENIERÍA CIVIL
LABORATORIO DE MECÁNICA DE SUELOS, CONCRETO Y ASFALTOS

PESOS UNITARIOS

NTP 400.017 - ASTM C - 29 AASHTO T - 19

TESIS : "DISEÑO DE CONCRETO PERMEABLE CON ADICIÓN DE PLASTIFICANTE PARA MEJORAR LA RESISTENCIA A LA COMPRESIÓN COMO ALTERNATIVA PARA EL DRENAJE PLUVIAL EN JULIACA 2021"
SOLICITANTE : Bach. CUSI CUSI, EDWIN
Bach. TICONA ALI, ALEX HERMENEGILDO
CANTERA : ISLA
LUGAR : SALIDA LAMPA - ANEXO ILO ILO - DISTRITO DE JULIACA - DEPARTAMENTO DE PUNO
FECHA : 05 DE NOVIEMBRE DEL 2021

DENSIDAD MINIMA AGREGADO (GRAVA)

PESO DEL MOLDE	**7205 gr**	**7205 gr**	**7205 gr**
VOLUMEN DEL MOLDE	**3383 cm3**	**3383 cm3**	**3383 cm3**
COLOCACION DE MUESTRA A MOLDE	**CAIDA LIBRE**	**CAIDA LIBRE**	**CAIDA LIBRE**
PESO DEL MOLDE + MUESTRA SUELTA	12205.00 gr	12165.00 gr	12180.00 gr
PESO DE LA MUESTRA SUELTA	5000.00 gr	4960.00 gr	4975.00 gr
DENSIDAD MINIMA DE LA MUESTRA SECA	**1.478 gr/cm3**	**1.466 gr/cm3**	**1.471 gr/cm3**
PROMEDIO		**1.472 gr/cm3**	

DENSIDAD MINIMA AGREGADO (GRAVA)

PESO DEL MOLDE	**7205 gr**	**7205 gr**	**7205 gr**
VOLUMEN DEL MOLDE	**3383 cm3**	**3383 cm3**	**3383 cm3**
Nº DE CAPAS	**3**	**3**	**3**
Nº DE GOLPES POR CAPA	**25**	**25**	**25**
PESO DEL MOLDE + MUESTRA COMPACTADA	12445.00 gr	12490.00 gr	12475.00 gr
PESO DE LA MUESTRA COMPACTADA	5240.00 gr	5285.00 gr	5270.00 gr
DENSIDAD MAXIMA DE LA MUESTRA SECA	**1.549 gr/cm3**	**1.562 gr/cm3**	**1.558 gr/cm3**
PROMEDIO		**1.556 gr/cm3**	

OBSERVACIONES: LAS MUESTRAS FUERON PUESTAS EN LABORATORIO POR EL SOLICITANTE

LABORATORIO
M.S.C.A.
JEFATURA

UANCV - FICP
CAP INGENIERÍA CIVIL
Mgtr. José Antonio Paredes Vera
CIP 62734

B.N° 005-268345

UNIVERSIDAD ANDINA "NÉSTOR CÁCERES VELÁSQUEZ"
FACULTAD DE INGENIERÍAS Y CIENCIAS PURAS
ESCUELA PROFESIONAL DE INGENIERÍA CIVIL
LABORATORIO DE MECÁNICA DE SUELOS, CONCRETO Y ASFALTOS

CONTENIDO DE HUMEDAD

ASTM D-2216 MTC E108-2000

TESIS : "DISEÑO DE CONCRETO PERMEABLE CON ADICIÓN DE PLASTIFICANTE PARA MEJORAR LA RESISTENCIA A LA COMPRESIÓN COMO ALTERNATIVA PARA EL DRENAJE PLUVIAL EN JULIACA 2021"
SOLICITANTE : Bach. CUSI CUSI, EDWIN
Bach. TICONA ALI, ALEX HERMENEGILDO
CANTERA : ISLA
LUGAR : SALIDA LAMPA - ANEXO ILO ILO - DISTRITO DE JULIACA - DEPARTAMENTO DE PUNO
FECHA : 05 DE NOVIEMBRE DEL 2021

MUESTRA : ARENA	
N° DE TARRO	1
PESO DE LA MUESTRA HUMEDA + TARRO (gr.)	427.06
PESO DE LA MUESTRA SECA + TARRO (gr.)	412.83
PESO DEL TARRO (gr.)	55.95
PESO DE LAMUESTRA HUMEDA (gr.)	**371.11**
PESO DE LA MUESTRA SECO (gr.)	**356.88**
PESO DEL AGUA (gr.)	**14.23**
% HUMEDAD	**3.99**

MUESTRA : GRAVA	
N° DE TARRO	2
PESO DE LA MUESTRA HUMEDA + TARRO (gr.)	471.75
PESO DE LA MUESTRA SECA + TARRO (gr.)	460.19
PESO DEL TARRO (gr.)	59.79
PESO DE LAMUESTRA HUMEDA (gr.)	**411.96**
PESO DE LA MUESTRA SECO (gr.)	**400.40**
PESO DEL AGUA (gr.)	**11.56**
% HUMEDAD	**2.89**

OBSERVACIONES:
* LAS MUESTRAS FUERON PUESTAS EN LABORATORIO POR EL SOLICITANTE.

LABORATORIO
M.S.C.A.
JEFATURA

UANCV - FICP
CAP INGENIERÍA CIVIL
Mgtr. José Antonio Paredes Vera
CIP 62794

B.N° 005-268345

UNIVERSIDAD ANDINA "NÉSTOR CÁCERES VELÁSQUEZ"
FACULTAD DE INGENIERÍAS Y CIENCIAS PURAS
ESCUELA PROFESIONAL DE INGENIERÍA CIVIL
LABORATORIO DE MECÁNICA DE SUELOS, CONCRETO Y ASFALTOS

RESISTENCIA AL DESGASTE "ABRASIÓN LOS ÁNGELES"

NORMAS ASTM C 131, AASTHO (DESIGNACION) T - 26

TESIS : "DISEÑO DE CONCRETO PERMEABLE CON ADICIÓN DE PLASTIFICANTE PARA MEJORAR LA RESISTENCIA A LA COMPRESIÓN COMO ALTERNATIVA PARA EL DRENAJE PLUVIAL EN JULIACA 2021"
SOLICITANTE : Bach. CUSI CUSI, EDWIN
Bach. TICONA ALI, ALEX HERMENEGILDO
MUESTRA : AGREGADO NATURAL
CANTERA : ISLA
UBICACIÓN : SALIDA LAMPA-SECTOR ILO ILO - JULIACA
FECHA : 03 DE NOVIEMBRE DEL 2021

TIPO DE AGREGADO: FINO: ☐ GRUESO: ☒ OTROS: ☐

MUESTRA OBTENIDA POR: CUARTEO: ☒ DIVISOR DE MUESTRAS: ☐

NUMERO DE REVOLUCIONES: 500 ☒ 1000 ☐

CARGA ABRASIVA: 12 ESFERAS

PESO SECO INICIAL DE LA MUESTRA: Wi = 5000 gr.

PESO SECO FINAL RETENIDA EN EL CEDAZO Nº 12: Wf = 3709 gr.

PESO DEL MATERIAL QUE PASA EL CEDAZO Nº 12: = 1291 gr.

PORCENTAJE DE PÉRDIDA:

$$De = \frac{W_i - W_F}{W_i} \times 100$$

De = **25.82** %

OBSERVACIONES:

* **GRADACIÓN : "A", 1 1/2" - 1" = 1250 gr. , 1" - 3/4" = 1250 gr. , 3/4" - 1/2" = 1250 gr. , 1/2" - 3/8" = 1250 gr.**
* **TIENE UNA RESISTENCIA AL DESGASTE DE 74.18 % Y PÉRDIDA DE : 25.82 %**
* **NORMA AASTHO (DESIGNACIÓN) T - 26, ASTM -C-131**

* **LA MUESTRA FUE PUESTA Y ETIQUETADA EN EL LABORATORIO POR EL SOLICITANTE.**

LABORATORIO M.S.C.A. JEFATURA

UANCV - FICP
CAP INGENIERÍA CIVIL
Mgtr. José Antonio Paredes Vera
CIP 62794

B.N° 005-268345

UNIVERSIDAD ANDINA "NÉSTOR CÁCERES VELÁSQUEZ"
FACULTAD DE INGENIERÍAS Y CIENCIAS PURAS
ESCUELA PROFESIONAL DE INGENIERÍA CIVIL
LABORATORIO DE MECÁNICA DE SUELOS, CONCRETO Y ASFALTOS

DISEÑO DE MEZCLA F'c = 175 Kg./cm.^{2}

TESIS : "DISEÑO DE CONCRETO PERMEABLE CON ADICIÓN DE PLASTIFICANTE PARA MEJORAR LA RESISTENCIA A LA COMPRESIÓN COMO ALTERNATIVA PARA EL DRENAJE PLUVIAL EN JULIACA 2021"
SOLICITANTE : Bach. CUSI CUSI, EDWIN
Bach. TICONA ALI, ALEX HERMENEGILDO
CANTERA : ISLA
UBICACIÓN : SALIDA LAMPA - ANEXO ILO ILO - DISTRITO DE JULIACA - DEPARTAMENTO DE PUNO
FECHA : 05 DE NOVIEMBRE DEL 2021

PROCESO DE DISEÑO:

NORMAS: ACI 211.1.74
ACI 211.1.81

El requerimiento promedio de resistencia a la compresión F'c = **175** Kg./cm.² a los 28 días
entonces la resistencia promedio F'cr = 245 Kg./cm.²

Las condiciones de colocación permiten un asentamiento de 3" a 4" (76.2 mm. A 101.6 mm.).

Dado el uso del agregado grueso, se utilizará el único agregado de calidad satisfactoria y económicamente disponible, el cual cumple con las especificaciones. Cuya graduación para el diámetro máximo nominal es de: **3/4"** (19.05mm)

Además se indica las pruebas de laboratorio para los agregados realizadas previamente:

RESULTADOS DE LABORATORIO

CARACTERÍSTICAS FÍSICAS	AGREGADO GRUESO GRAVA	AGREGADO FINO ARENA
P.e de Sólidos		
P.e SSS	2.53	2.55
P.e Bulk		
P.U. Varillado	1556	1644
P.U. Suelto	1472	1586
% de Absorción	1.72	2.76
% de Humedad Natural	2.89	3.99
Modulo de Fineza	-	3.34

Los cálculos aparecerán únicamente en forma esquemática:

1, El asentamiento dado es de 3" a 4" (76.2 mm. A 101.6 mm.).
2, Se usará el agregado disponible en la localidad, el cual posee un diámetro nomina 3/4" (19.05mm)
3, Puesto que no se utilizará incorporador de aire, pero la estructura estará expuesta a intemperismo severo, la cantidad aproximada de agua de mezclado que se empleará para producir el asentamiento indicado será de: **205** Lt/m3
4, Como el concreto estará sometido a intemperismo severo se considera un contenido de aire atrapado de: **2.0** %
5, Como se prevee que el concreto no será atacado por sulfatos, entonces las relación agua/cemento (a/c) será de: **0.62**
6, De acuerdo a la información obtenida en los items 3 y 4 el requerimiento de cemento será de:

(205 Lt/m3) / (0.62) = 331 Kg/m3

LABORATORIO
M.S.C.A.
JEFATURA

UANCV - FICP
CAP INGENIERÍA CIVIL
Mgtr. José Antonio Paredes Vera
CIP 62754

B.N° 005-268345

7, De acuerdo al módulo de fineza del agregado fino = 3.34 el peso específico unitario del agregado grueso varillado-compactado de 1556 Kg/m3 y un agregado grueso con tamaño máximo nominal de 3/4" (19.05mm) se recomienda el uso de **0.566** m3 de agregado grueso por m3 de concreto. Por tanto el peso seco del agregado grueso será de:

(0.5655)*(1556) = 880 Kg/m3

8, Una vez determinadas las cantidades de agua, cemento y agregado grueso, los materiales resultantes para completar un m3 de concreto consistirán en arena y aire atrapado. La cantidad de arena requerida se puede determinar en base al volumen absoluto como se muestra a continuación.

Con las cantidades de agua, cemento y agregado grueso ya determinadas y considerando el contenido aproximado de aire atrapado, se puede calcular el contenido de arena como sigue:

Volúmen absoluto de agua = (205) / (1000) = 0.205
Volúmen absoluto de cemento = (331) / (2.88 * 1000) = 0.115
Volúmen absoluto de agregado grueso = (880) / (2.53 * 1000) = 0.348
Volúmen de aire atrapado = (2.0) / (100) = 0.020
Volúmen sub total = 0.688

Volúmen absoluto de arena

Por tanto el peso requerido de arena seca será de: = (1.000 - 0.688) = 0.312 m3

(0.312) * (2.55) * 1000 = 794 Kg/m3

9, De acuerdo a las pruebas de laboratorio se tienen % de humedad, por las que se tiene que ser corregidas los pesos de los agregados:

Agregado grueso húmedo (880) * (1.028871) = 906 Kg.
Agregado Fino húmedo (794) * (1.0399) = 826 Kg.

10, El agua de absorción no forma parte del agua de mezclado y debe excluirse y ajustarse por adición de agua. De esta manera la cantidad de agua efectiva es:

$$205 - 880 * \left(\frac{2.89 - 1.72}{100} \right) - 794 \left(\frac{3.99 - 2.76}{100} \right) = 185$$

DOSIFICACIÓN

AGREGADO	DOSIFICACIÓN EN PESO SECO	PROPORCIÓN EN VOLUMEN	DOSIFICACIÓN EN PESO HÚMEDO	PROPORCIÓN EN VOLUMEN
	(Kg/m3)	PESO SECO	(Kg/m3)	PESO HÚMEDO
Cemento	331	1.00	331	1.00
Agua	205	0.62	185	0.56
Agreg. Grueso	880	2.66	906	2.74
Agreg. Fino	794	2.40	826	2.50
Aire	2.0 %		2.0 %	

7.78 BOLSAS / m3 DE CEMENTO

DOSIFICACIÓN POR PESO:

Cemento	:	42.50 Kg.
Agregado fino húmedo	:	106.12 Kg.
Agregado grueso húmedo	:	116.41 Kg.
Agua efectiva	:	23.78 Kg.

LABORATORIO
M.S.C.A.
JEFATURA

UANCV - FICP
CAP INGENIERÍA CIVIL
Mgtr. José Antonio Paredes Jer.
CIP 62754

B.N° 005-268345

DOSIFICACIÓN POR TANDAS:

Para Mezcladora de 9 pies3

1.0 Bolsa de Cemento:		Redondeo	
- **2.36**	p3 de Arena	**2.4**	p3 de Arena
- **2.80**	p3 de Grava	**2.8**	p3 de Grava
- **24**	Lt de Agua	**24**	Lt de Agua

RECOMENDACIONES

Debido a las características de los agregados, se recomienda que la dosificación tanto de la arena como de la grava se realice en forma separada, tal como se indica en el item DOSIFICACION POR TANDAS.

* Se debera de hacer las correcciones del W% del A.F. y A.G.

OBSERVACIONES:

* LAS MUESTRAS FUERON PUESTAS EN EL LABORATORIO POR EL SOLICITANTE.

LABORATORIO
M.S.C.A.
JEFATURA

UANCV - FICP
CAP INGENIERÍA CIVIL

Mgtr. José Antonio Paredes Vera
CIP 62754

B.N° 005-268345

UNIVERSIDAD ANDINA "NÉSTOR CÁCERES VELÁSQUEZ"
FACULTAD DE INGENIERÍAS Y CIENCIAS PURAS
ESCUELA PROFESIONAL DE INGENIERÍA CIVIL
LABORATORIO DE MECÁNICA DE SUELOS, CONCRETO Y ASFALTOS

PRUEBA DE RESISTENCIA A LA COMPRESIÓN

NTP 339.034

TESIS : "DISEÑO DE CONCRETO PERMEABLE CON ADICIÓN DE PLASTIFICANTE PARA MEJORAR LA RESISTENCIA A LA COMPRESIÓN COMO ALTERNATIVA PARA EL DRENAJE PLUVIAL EN JULIACA 2021"

SOLICITANTE : Bach. CUSI CUSI, EDWIN
Bach. TICONA ALI, ALEX HERMENEGILDO

MUESTRA : PROBETAS A LOS 7 DÍAS

LUGAR : LABORATORIO DE MECÁNICA DE SUELOS CONCRETO Y ASFALTO U.A.N.C.V. - JULIACA

FECHA : 06 DE DICIEMBRE DEL 2021

N°	DESCRIPCIÓN DE LA MUESTRA	CARGA	Ø	AREA	ESF. ROTURA	F'C	FECHA	FECHA	EDAD	%
		Kg	cm	cm2	Kg/cm2	Kg/cm2	VACIADO	ROTURA	DIAS	
	MUESTRA SIN PLASTIFICANTE									
1	PROBETAS DE PRUEBA 14.96 x 30.0 cm MUESTRA N° 01	15668.00	14.96	175.77	89.14	175	08/11/2021	15/11/2021	7	**50.94%**
2	PROBETAS DE PRUEBA 14.98 x 30.0 cm MUESTRA N° 02	15985.00	14.98	176.24	90.70	175	08/11/2021	15/11/2021	7	**51.83%**
3	PROBETAS DE PRUEBA 15.00 x 30.0 cm MUESTRA N° 03	16102.00	15.00	176.71	91.12	175	08/11/2021	15/11/2021	7	**52.07%**
4	PROBETAS DE PRUEBA 15.02 x 30.0 cm MUESTRA N° 04	14857.00	15.02	177.19	83.85	175	08/11/2021	15/11/2021	7	**47.91%**
5	PROBETAS DE PRUEBA 15.01 x 30.0 cm MUESTRA N° 05	15874.00	14.97	176.01	90.19	175	08/11/2021	15/11/2021	7	**51.54%**
							PROMEDIO			**50.86%**
	MUESTRA CON PLASTIFICANTE									
1	PROBETAS DE PRUEBA 15.00 x 30.0 cm MUESTRA N° 01	17256.00	15.00	176.71	97.65	175	08/11/2021	15/11/2021	7	**55.80%**
2	PROBETAS DE PRUEBA 14.97 x 30.0 cm MUESTRA N° 02	16562.00	14.97	176.01	94.10	175	08/11/2021	15/11/2021	7	**53.77%**
3	PROBETAS DE PRUEBA 15.00 x 30.0 cm MUESTRA N° 03	17125.00	15.00	176.71	96.91	175	08/11/2021	15/11/2021	7	**55.38%**
4	PROBETAS DE PRUEBA 15.01 x 30.0 cm MUESTRA N° 04	15456.00	15.01	176.95	87.35	175	08/11/2021	15/11/2021	7	**49.91%**
5	PROBETAS DE PRUEBA 14.98 x 30.0 cm MUESTRA N° 05	16857.00	14.98	176.24	95.65	175	08/11/2021	15/11/2021	7	**54.66%**
							PROMEDIO			**53.90%**

OBSERVACIONES:

1.- LAS MUESTRAS FUERON PUESTAS EN EL LABORATORIO POR EL SOLICITANTE

UANCV - FICP
CAP INGENIERÍA CIVIL
Mgtr. José Antonio Paredes Vera
CIP 82794

B. N° 005-268345

UNIVERSIDAD ANDINA "NÉSTOR CÁCERES VELÁSQUEZ"
FACULTAD DE INGENIERÍAS Y CIENCIAS PURAS
ESCUELA PROFESIONAL DE INGENIERÍA CIVIL
LABORATORIO DE MECÁNICA DE SUELOS, CONCRETO Y ASFALTOS

PRUEBA DE RESISTENCIA A LA COMPRESIÓN

NTP 339.034

TESIS : "DISEÑO DE CONCRETO PERMEABLE CON ADICIÓN DE PLASTIFICANTE PARA MEJORAR LA RESISTENCIA A LA COMPRESIÓN COMO ALTERNATIVA PARA EL DRENAJE PLUVIAL EN JULIACA 2021"

SOLICITANTE : Bach. CUSI CUSI, EDWIN
Bach. TICONA ALI, ALEX HERMENEGILDO

MUESTRA : PROBETAS A LOS 14 DÍAS

LUGAR : LABORATORIO DE MECÁNICA DE SUELOS CONCRETO Y ASFALTO U.A.N.C.V. - JULIACA

FECHA : 06 DE DICIEMBRE DEL 2021

Nº	DESCRIPCIÓN DE LA MUESTRA	CARGA Kg	Ø cm	AREA cm2	ESF. ROTURA Kg/cm2	F'C Kg/cm2	FECHA VACIADO	FECHA ROTURA	EDAD DIAS	%
	MUESTRA SIN PLASTIFICANTE									
1	PROBETAS DE PRUEBA 14.99 x 30.0 cm MUESTRA N° 01	23232.00	14.99	176.48	131.64	175	08/11/2021	22/11/2021	14	**75.22%**
2	PROBETAS DE PRUEBA 14.98 x 30.0 cm MUESTRA N° 02	22978.00	15.01	176.95	129.86	175	08/11/2021	22/11/2021	14	**74.20%**
3	PROBETAS DE PRUEBA 15.00 x 30.0 cm MUESTRA N° 03	20859.00	15.00	176.71	118.04	175	08/11/2021	22/11/2021	14	**67.45%**
4	PROBETAS DE PRUEBA 14.98 x 30.0 cm MUESTRA N° 04	23857.00	14.98	176.24	135.37	175	08/11/2021	22/11/2021	14	**77.35%**
5	PROBETAS DE PRUEBA 15.01 x 30.0 cm MUESTRA N° 05	23548.00	14.98	176.24	133.61	175	08/11/2021	22/11/2021	14	**76.35%**
							PROMEDIO			74.12%
	MUESTRA CON PLASTIFICANTE									
1	PROBETAS DE PRUEBA 15.00 x 30.0 cm MUESTRA N° 01	24521.00	15.00	176.71	138.76	175	08/11/2021	22/11/2021	14	**79.29%**
2	PROBETAS DE PRUEBA 15.00 x 30.0 cm MUESTRA N° 02	25857.00	15.00	176.71	146.32	175	08/11/2021	22/11/2021	14	**83.61%**
3	PROBETAS DE PRUEBA 15.02 x 30.0 cm MUESTRA N° 03	23256.00	15.02	177.19	131.25	175	08/11/2021	22/11/2021	14	**75.00%**
4	PROBETAS DE PRUEBA 14.98 x 30.0 cm MUESTRA N° 04	24897.00	14.98	176.24	141.27	175	08/11/2021	22/11/2021	14	**80.72%**
5	PROBETAS DE PRUEBA 15.01 x 30.0 cm MUESTRA N° 05	24221.00	15.01	176.95	136.88	175	08/11/2021	22/11/2021	14	**78.22%**
							PROMEDIO			79.37%

OBSERVACIONES:

1.- LAS MUESTRAS FUERON PUESTAS EN EL LABORATORIO POR EL SOLICITANTE

UANCV - FICP
CAP INGENIERÍA CIVIL
Mgtr. José Antonio Paredes Vera
CIP 62794

B. N° 005-268345

CONGEOMAT
LABORATORIO DE SUELOS Y MATERIALES

DISEÑO DE CONCRETO PERMEABLE CON ADICIÓN DE PLASTIFICANTE PARA MEJORAR LA RESISTENCIA A LA COMPRESIÓN COMO ALTERNATIVA PARA EL DRENAJE PLUVIAL EN JULIACA 2021

CERTIFICADOS
DE
ENSAYOS

PUNO – PERÚ
2021

ROTURA DE PROBETAS

NTP 339.034 (ASTM C 39)

DATOS GENERALES

PROYECTO: DISEÑO DE CONCRETO PERMEABLE CON ADICIÓN DE PLASTIFICANTE PARA MEJORAR LA RESISTENCIA A LA COMPRESIÓN COMO ALTERNATIVA PARA EL DRENAJE PLUVIAL EN JULIACA 2021

UBICACIÓN: DISTRITO DE JULIACA

SOLICITANTES: EDWIN, CUSI CUSI Y ALEX HERMENEGILDO, TICONA ALI

CÓDIGO CLIENTE: C - 0161- 21

REGISTRO: E-0001-21

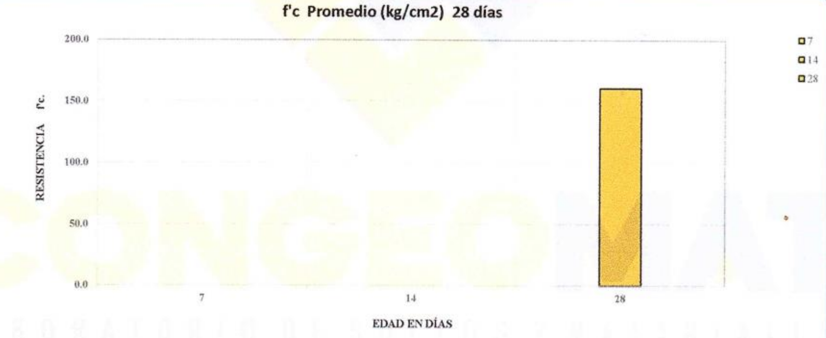
FECHA DE ROTURA: 06-dic-22

DATOS DE LA MUESTRA

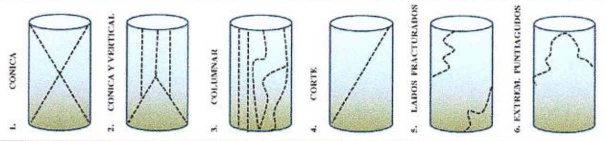
MATERIAL: CONCRETO

RESISTENCIA A LA COMPRESIÓN DE ESPECIMENES CILINDRICOS DE CONCRETO

Prob. Nro	Material	Descripción	Diseño (kg/cm2)	Fecha Moldeo	Fecha Rotura	Edad días	dprom (cm)	Área (cm2)	Carga Máx. (KN.)	Carga Máx. (Kg.)	f'c Obtenido (Kg./cm^2)	f'c Promed. (Kg/cm^2)	Tipo falla
001 - A	CONCRETO PERMEABLE	SIN PLASTIFICANTE	175	08-nov-22	06-dic-22	28	15.00	176.7	274.5	27,970	158.28	160.8	5
001 - B							14.99	176.5	288.9	29,440	166.82		5
001 - C							15.01	177.0	281.3	28,660	161.97		5
001 - D							14.98	176.2	286.5	29,190	165.62		5
001 - E							15.02	177.2	263.5	26,850	151.54		5



Prob. Nro	Tipo de Falla
001 - A	5
001 - B	5
001 - C	5
001 - D	5
001 - E	5



OBSERVACIONES:

- Las muestras fueron proporcionadas por los solicitantes

CONGEOMAT S.R.L.
John Percy Paricahua Tintaya
TEC DE SUELOS Y PAVIMENTOS

CONGEOMAT S.R.L
Alberth Ysidro Quispe Bustinza
ING DE SUELOS Y PAVIMENTOS
C.I.P Nº 181300

ROTURA DE PROBETAS

NTP 339.034 (ASTM C 39)

Código : F - 001
Versión : 3.0
Aprobado : ene-21

DATOS GENERALES

PROYECTO: DISEÑO DE CONCRETO PERMEABLE CON ADICIÓN DE PLASTIFICANTE PARA MEJORAR LA RESISTENCIA A LA COMPRESIÓN COMO ALTERNATIVA PARA EL DRENAJE PLUVIAL EN JULIACA 2021

UBICACIÓN: DISTRITO DE JULIACA

SOLICITANTES: EDWIN, CUSI CUSI Y ALEX HERMENEGILDO, TICONA ALI

CÓDIGO CLIENTE: C - 0161- 21

REGISTRO: E-0002-21

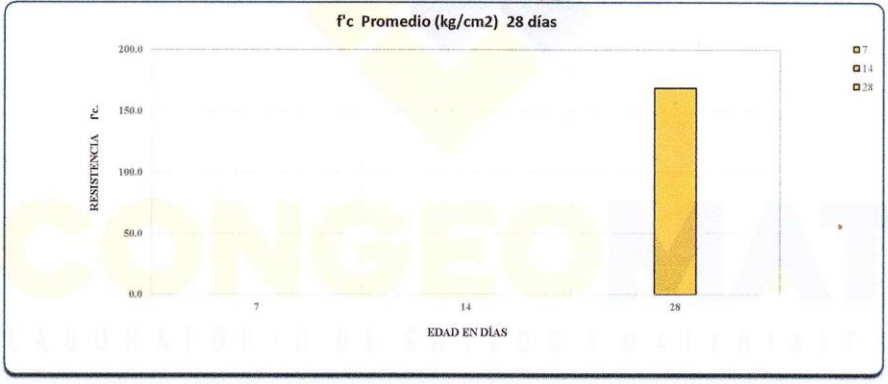
FECHA DE ROTURA: 06-dic-22

DATOS DE LA MUESTRA

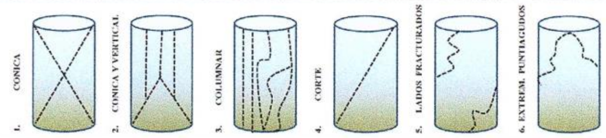
MATERIAL: CONCRETO

RESISTENCIA A LA COMPRESIÓN DE ESPECIMENES CILINDRICOS DE CONCRETO

Prob. Nro	Material	Descripción	Diseño (kg/cm2)	Fecha Moldeo	Fecha Rotura	Edad dias	dprom (cm)	Área (cm2)	Carga Máx. (KN.)	Carga Máx. (Kg.)	f'c Obtenido (Kg./cm^2)	f'c Promed. (Kg/cm^2)	Tipo falla
002 - A	CONCRETO PERMEABLE	CON PLASTIFICANTE	175	08-nov-22	06-dic-22	28	14.99	176.5	294.0	29,960	169.77	168.7	5
002 - B							15.00	176.7	299.8	30,550	172.88		5
002 - C							15.00	176.7	291.1	29,660	167.84		5
002 - D							15.02	177.2	281.3	28,660	161.75		5
002 - E							14.98	176.2	296.0	30,160	171.13		5



Prob. Nro	Tipo de Falla
002 - A	5
002 - B	5
002 - C	5
002 - D	5
002 - E	5



OBSERVACIONES:

- Las muestras fueron proporcionadas por los solicitantes

CONGEOMAT S.R.L.
John Percy Paricahua Tintaya
TEC DE SUELOS Y PAVIMENTOS

CONGEOMAT S.R.L.
Alberth Ysidro Quispe Bustinza
ING DE SUELOS Y PAVIMENTOS
C.I.P N° 151300

CONGEOMAT
LABORATORIO DE SUELOS Y MATERIALES

DISEÑO DE CONCRETO PERMEABLE CON ADICIÓN DE PLASTIFICANTE PARA MEJORAR LA RESISTENCIA A LA COMPRESIÓN COMO ALTERNATIVA PARA EL DRENAJE PLUVIAL EN JULIACA 2021

CERTIFICADO DE CALIBRACIÓN

PUNO – PERÚ
2021

Arsou Group
Laboratorio de Metrología

CERTIFICADO DE CALIBRACIÓN
N° 0748-046-2021

Fecha de emisión	2021/11/13
Solicitante	CONSULTORES EN GEOTECNIA Y MATERIALES SOCIEDAD COMERCIAL DE RESPONSABILIDAD LIMITADA
Dirección	JR. 16 DE DICIEMBRE MZ. A LOTE 30 PUNO - SAN ROMAN - JULIACA
Instrumento de medición	**PRENSA HIDRAULICA PARA CONCRETO**
Identificación	0748-046-2021
Marca	ARSOU
Modelo	PC2V
Serie	2073
Capacidad	120,000 KGF
Indicador	HIGHT WEIGTH
Serie	NO INDICA
Bomba	MANUAL
Procedencia	PERÚ
Lugar de calibración	Laboratorio de CONSULTORES EN GEOTECNIA Y MATERIALES SOCIEDAD COMERCIAL DE RESPONSABILIDAD LIMITADA
Fecha de calibración	2021/11/13

Método/Procedimiento de calibración

El procedimiento toma como referencia a la norma ISO 7500-1 "Metallic materials - Verification of static uniaxial testing machines", Se aplicaron dos series de carga al Sistema Digital mediante la misma prensa. En cada serie se registraron las lecturas de las cargas.

Este certificado de calibración documenta la trazabilidad a patrones nacionales o internacionales, que realizan las unidades de medida de acuerdo con el Sistema Internacional de Unidades (SI)

Los resultados son válidos en el momento de la calibración. Al solicitante le corresponde disponer en su momento recalibrar sus instrumentos a intervalos regulares, los cuales deben ser establecidos sobre la base de las características propias del instrumento, sus condiciones de uso, el mantenimiento realizado y conservación del instrumento de medición o de acuerdo a reglamentaciones vigentes.

ARSOU GROUP S.A.C. no se responsabiliza de los perjuicios que pueda ocasionar el uso inadecuado de este instrumento después de su calibración, ni de una incorrecta interpretación de los resultados de la calibración declarados en este documento.

Este certificado no podrá ser reproducido o difundido parcialmente, excepto con autorización previa por escrito de ARSOU GROUP S.A.C.

Arsou Group S.A.C
Laboratorio de Metrología

ARSOU GROUP S.A.C
Ing. Hugo Luis Arévalo Carnica
METROLOGIA

Patrones e Instrumentos auxiliares

Trazabilidad	Patrón Utilizado	Certificado de Calibración
Patrones de referencia de PUCP	Celda de Carga de 100 TN	INF-LE N° 175-21

Condiciones ambientales durante la calibración

Temperatura Ambiental	Inicial: 18,3 ºc	Final: 18,0 ºC
Humedad Relativa	Inicial: 87 %hr	Final: 87 %hr
Presión Atmosférica	Inicial: 1015 mbar	Final: 1015 mbar

Resultados

TABLA N° 01
CALIBRACION DE PRENSA HIDRAULICA PARA CONCRETO

SISTEMA DIGITAL "A" kg	SERIES DE VERIFICACIÓN PATRON (Kg)				PROMEDIO	ERROR	RPTBLD
	SERIE (1) kg	SERIE (2) kg	ERROR %	ERROR (2) %	"B" kN	Ep %	Rp %
10000	10000.0	9998	0.00	0.02	9999.0	-0.01	0.01
20000	20039.4	20041.1	0.20	0.21	20040.3	0.20	0.01
30000	30001	29998	0	-0.01	29999.5	0.00	0.01
40000	40078	40090	0.2	0.23	40084.0	0.21	0.02
50000	50998	49999	2	0	50498.5	1.00	1.40
60000	59998	60015	0	0.03	60006.5	0.01	0.02
70000	70045	70010	0.06	0.01	70027.5	0.04	0.04
80000	80045	79999	0.06	0.00	80022.0	0.03	0.04

NOTAS SOBRE CALIBRACION

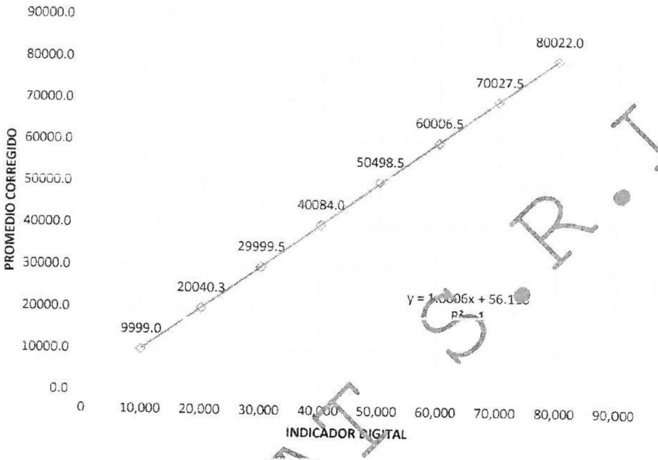
1. - La Calibración se hizo según el Método C de la norma ISO 7500-1
2.- Ep y Rp son el Error Porcentual y la Repetibilidad definidos en la citada Norma:
Ep = ((A-B) / B)* 100 Rp = Error(2) - Error(1)
3. - La norma exige que Ep y Rp no excedan el +/- 1.0 %

Arsou Group S.A.C
Laboratorio de Metrología

ARSOU GROUP S.A.C
Ing. Hugo Luis Arévalo Carnica
METROLOGÍA

Gráfica (Coeficiente de correlación y Ecuación de Ajuste

GRAFICO N° 01



Ecuación de ajuste:
Donde: **y = 1,0006x + 56,116**
Coeficiente Correlación **R^2 = 1**

X : Lectura de la pantalla (kg)
Y : fuerza promedio (kg)

Observaciones

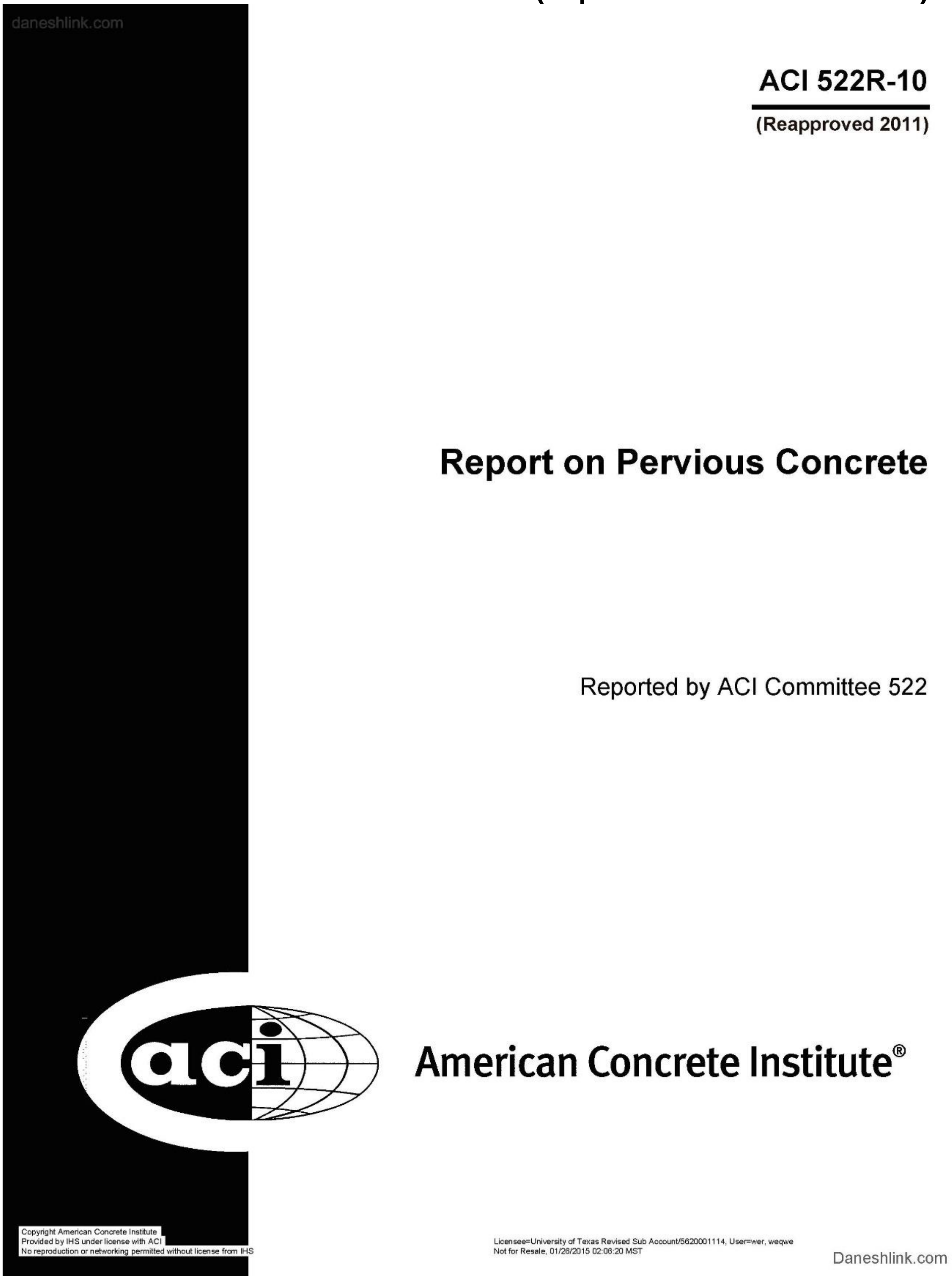
1. Antes de la calibración no se realizó ningún tipo de ajuste.

2. La incertidumbre de la medición ha sido calculada para un nivel de confianza de aproximadamente del 95 % con un factor de cobertura k=2
3. (*) Codigo indicado en una etiqueta adherida al instrumento.
4. Con fines de identificación se colocó una etiqueta autoadhesiva con la indicación "CALIBRADO"

ARSOU GROUP S.A.C
Ing. Hugo Luis Arevalo Carnica
METROLOGIA

Arsou Group S.A.C Laboratorio de Metrología

ANEXO 3. NORMA TÉCNICA ACI 522R-10 (Report On Pervious Concrete)



ACI 522R-10

(Reapproved 2011)

Report on Pervious Concrete

Reported by ACI Committee 522

American Concrete Institute®

First Printing
March 2010

American Concrete Institute®
Advancing concrete knowledge

Report on Pervious Concrete

The technical committees responsible for ACI committee reports and standards strive to avoid ambiguities, omissions, and errors in these documents. In spite of these efforts, the users of ACI documents occasionally find information or requirements that may be subject to more than one interpretation or may be incomplete or incorrect. Users who have suggestions for the improvement of ACI documents are requested to contact ACI. Proper use of this document includes periodically checking for errata at **www.concrete.org/committees/errata.asp** for the most up-to-date revisions.

ACI committee documents are intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. Individuals who use this publication in any way assume all risk and accept total responsibility for the application and use of this information.

All information in this publication is provided "as is" without warranty of any kind, either express or implied, including but not limited to, the implied warranties of merchantability, fitness for a particular purpose or non-infringement.

ACI and its members disclaim liability for damages of any kind, including any special, indirect, incidental, or consequential damages, including without limitation, lost revenues or lost profits, which may result from the use of this publication.

It is the responsibility of the user of this document to establish health and safety practices appropriate to the specific circumstances involved with its use. ACI does not make any representations with regard to health and safety issues and the use of this document. The user must determine the applicability of all regulatory limitations before applying the document and must comply with all applicable laws and regulations, including but not limited to, United States Occupational Safety and Health Administration (OSHA) health and safety standards.

Order information: ACI documents are available in print, by download, on CD-ROM, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised *ACI Manual of Concrete Practice* (MCP).

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
U.S.A.
Phone: 248-848-3700
Fax: 248-848-3701

www.concrete.org

ISBN 978-0-87031-364-6

ACI 522R-10

(Reapproved 2011)

Report on Pervious Concrete

Reported by ACI Committee 522

Matthew A. Offenberg
Chair

Don J. Wade
Vice Chair

Charles A. Weiss Jr.
Secretary

William L. Arent
Bob J. Banka
William D. Brant
Heather J. Brown
Javier Casto
Manoj Chopra
John Cook
Michael S. Davy
Norbert J. Delatte
Aly Ibrahim Eldarwish
Scott Erickson
Dale Fisher
Walter Flood
Bruce A. Glaspey
Liv Haselbach
Omer Heracklis
Daniel J. Huffman
John Kevern
Frank Lennox
Milan Lipensky
John R. Love III
Darmawan Ludirdja
Allen Luke
Brian Lutey
Kamyar C. Mahboub
Andrew Marks
Luis Mata
Narayanan Neithalath
Oon-Soo Ooi
Joseph E. Rottman
Thomas Rozsits
George W. Seegebrecht
David M. Suchorski
Diep T. Tu
Christopher Tull
Robert Louis Varner
W. Jason Weiss
Kevin Wolf
Peter T. Yen

This report provides technical information on pervious concrete's application, design methods, materials, properties, mixture proportioning, construction methods, testing, and inspection.

The term "pervious concrete" typically describes a near-zero-slump, open-graded material consisting of portland cement, coarse aggregate, little or no fine aggregate, admixtures, and water. The combination of these ingredients will produce a hardened material with connected pores, ranging in size from 0.08 to 0.32 in. (2 to 8 mm), that allow water to pass through easily. The void content can range from 15 to 35%, with typical compressive strengths of 400 to 4000 psi (2.8 to 28 MPa). The drainage rate of pervious concrete pavement will vary with aggregate size and density of the mixture, but will generally fall into the range of 2 to 18 gal./min/ft^2 (81 to 730 L/min/m^2). Pervious concrete is widely recognized as a sustainable building material, as it reduces stormwater runoff, improves stormwater quality, may recharge groundwater supplies, and can reduce the impact of the urban heat island effect.

Keywords: construction; design; drainage; green building; LEED® credit; permeability; pervious concrete pavement; stormwater; sustainability; testing.

CONTENTS

ACI 522R-10 supersedes ACI 522R-06 and was adopted and published March 2010.

CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

This report provides technical information on pervious concrete's application, design methods, materials, properties, mixture proportioning, construction methods, testing, and inspection.

The term "pervious concrete" typically describes a near-zero-slump, open-graded material consisting of portland cement, coarse aggregate, little or no fine aggregate, admixtures, and water. The combination of these ingredients will produce a hardened material with connected pores (Fig. 1.1), ranging in size from 0.08 to 0.32 in. (2 to 8 mm), that allow water to pass through easily. The void content can range from 15 to 35%, with typical compressive strengths of 400 to 4000 psi (2.8 to 28 MPa). The drainage rate of pervious concrete pavement will vary with aggregate size and density of the mixture, but will generally fall into the range of 2 to 18 gal./min/ft^2 (81 to 730 L/min/m^2) or 192 to 1724 in./h (0.14 to 1.22 cm/s).

1.2—Scope

Concern has been growing in recent years toward reducing the pollutants in water supplies and the environment. In the

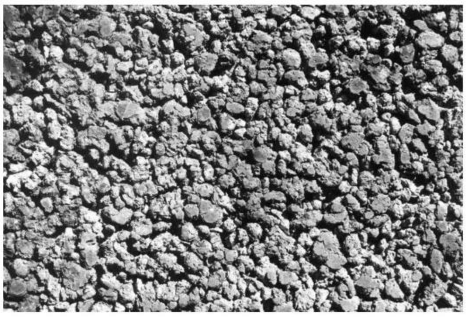


Fig. 1.1—Pervious concrete pavement texture on parking lot.

1960s, engineers realized that runoff from developed real estate had the potential to pollute surface and groundwater supplies. Further, as land is developed, runoff leaves the site in higher rates and volumes, leading to downstream flooding and bank erosion. Pervious concrete pavement reduces the impact of development by reducing or eliminating stormwater runoff rates and protecting water supplies.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A = area of the pavement, acre (m^2)
b = solid volume of coarse aggregate in a unit volume of concrete, ft^3 (m^3)
b_o = solid volume of coarse aggregate in a unit volume of coarse aggregate, ft^3 (m^3)
b/b_o = dry-rodded volume of coarse aggregate in a unit volume of concrete
C = runoff coefficient
c = cement content, lb (kg)
d_1 = thickness of the pavement, ft (m)
d_2 = thickness of the subgrade, ft (m)
f_c' = specified compressive strength of concrete, psi (MPa)
f_r = modulus of rupture of concrete, psi (MPa)
t = time, seconds
h_1 = initial head, in. (mm)
h_2 = final head, in. (mm)
k = permeability, in./s (mm/s)
p_1 = percentage of void space in the pavement
p_2 = percentage of void space in the subgrade
R = pressure reflection coefficient
V_a = aggregate volume, ft^3 (m^3)
V_c = cement volume, ft^3 (m^3)
V_P = paste volume; total of cement and water volume, ft^3 (m^3)
V_p = available storage in pavement, ft^3 (m^3)
V_r = required storage volume, ft^3 (m^3)
V_s = available storage in subgrade, ft^3 (m^3)
V_s = total solid volume of aggregate, cement, and water, ft^3 (m^3)
V_{tot} = total volume, ft^3 (m^3)
V_w = water volume, ft^3 (m^3)
W_a = dry aggregate weight, lb (kg)
W_{ssd} = saturated surface-dry weight, lb (kg)
w = water content, lb (kg)
α = absorption coefficient

2.2—Definitions

ACI provides a comprehensive list of acceptable definitions through an online resource, "ACI Concrete Terminology," http://terminology.concrete.org. Definitions provided here complement that resource.

concrete, pervious—hydraulic cement concrete proportioned with sufficient interconnected voids that result in a highly permeable material, allowing water to readily pass.

impervious area—an area covered by a material that prevents precipitation from infiltrating soils and recharging groundwater supplies.

pavement, pervious—a pavement comprising material with sufficient continuous voids to allow water to pass from the surface to the underlying layers.

percolation rate—the rate, usually expressed as inches per hour or inches per day, at which water moves through pervious concrete.

porosity—the volume of open and connected interstitial void space in pervious concrete.

raveling—the wearing away of the concrete surface caused by the dislodging of aggregate particles.

runoff—water from rain or snow that is not absorbed into the ground but instead flows over less pervious surfaces into streams and rivers.

surface course—the top layer of a concrete pavement structure.

void content—the ratio of the volume of voids, including both entrapped and entrained air, to the total volume expressed as a percentage.

CHAPTER 3—APPLICATIONS

3.1—General

Pervious concrete has been used in a wide range of applications, including:

- Pervious pavement for parking lots (Fig. 3.1);
- Rigid drainage layers under exterior mall areas;
- Greenhouse floors to keep the floor free of standing water;
- Structural wall applications where lightweight or better thermal insulation characteristics, or both, are required;
- Pavements, walls, and floors where better acoustic absorption characteristics are desired;
- Base course for streets, roads, driveways, and airports;
- Surface course for parks and tennis courts;
- Floors for zoo areas and animal barns and stalls;
- Bridge embankments;
- Swimming pool decks;

Fig. 3.1—Parking lot built with pervious concrete pavement.

- Beach structures and seawalls;
- Sewage treatment plant sludge beds;
- Solar energy storage systems;
- Wall linings for drilled water wells; and
- Artificial reefs where the open structure of pervious concrete mimics the reef structure.

Typically, unreinforced pervious concrete is used in all these applications because of the high risk of reinforcing steel corrosion due to the open pore structure of the material.

3.2—Building applications: history

Pervious concrete has been used in building construction since at least the middle of the nineteenth century (Francis 1965). Throughout this chapter, the term "pervious concrete" is used to describe the material, but in the references and historically, it may have been described as no-fines concrete or gap-graded concrete. European countries have used pervious concrete in different modes: cast-in-place load-bearing walls in single- and multistory houses and, in some instances, in high-rise buildings, prefabricated panels, and steam-cured blocks. In 1852, pervious concrete was first used in the construction of two houses in the United Kingdom (UK). This concrete consisted of only coarse gravel and cement. It is not mentioned in the published literature again until 1923, when a group of 50 two-story houses were built with clinker aggregate in Edinburgh, Scotland. In the late 1930s, the Scottish Special Housing Association Limited adopted the use of pervious concrete for residential construction. By 1942, pervious concrete had been used to build over 900 houses.

From 1939 to 1945, the havoc of World War II left almost all of Europe with vast housing needs, which encouraged the development of new or previously unused methods of building construction. Notably among them was pervious concrete (Malhotra 1969). Pervious concrete used less cement per unit volume of concrete as compared with conventional concrete, and the material was advantageous where manpower was scarce or expensive. Over the years, the pervious concrete system contributed substantially to the production of new houses in the UK, Germany, Holland, France, Belgium, Scotland, Spain, Hungary, Venezuela, West Africa, the Middle East, Australia, and Russia. Germany used this system because disposal of large quantities of brick rubble was a problem after the war, leading to research into the properties of pervious concrete. Elsewhere, the unprecedented demand for brick and the subsequent inability of the brick-making industry to provide an adequate supply, led to the adoption of pervious concrete as a building material. Similarly in Scotland, between 1945 and 1956, many homes were built with pervious concrete. This was mainly due to the presence of unlimited supplies of hard aggregates and the absence of good facing bricks. The first reported use of pervious concrete in Australia was as early as 1946.

Before World War II, production of pervious concrete was confined to two-story homes. After 1946, however, pervious concrete was used for a much broader range of applications. It was specified as a material for load-bearing elements in buildings up to 10 stories tall (Francis 1965).

Fig. 3.2—Pervious concrete pavement used within the drip line of tree.

Pervious concrete was extensively used for industrial, public, and domestic buildings in areas north of the Arctic Circle because traditional building materials proved impracticable. Examples of these impracticalities include the high transportation costs of brick, fire hazards of timber, and poor thermal insulation properties of plain concrete (Malhotra 1976).

Although pervious concrete has been used in Europe and Australia for the past 60 years, its use as a building material in North America has been extremely limited. One reason for this limited use is, after World War II, North America did not experience a materials shortage as much as Europe.

In Canada, the first reported use of pervious concrete was in 1960. Pervious concrete was used in the construction of some houses in Toronto and on a nonstructural basis in a federal building in Ottawa.

3.3—Pavement applications

Pervious concrete pavements' advantages over conventional concrete pavements include:

- Controlling stormwater pollution at the source;
- Increasing facilities for parking by eliminating the need for water-retention areas;
- Controlling stormwater runoff;
- Reducing hydroplaning on road and highway surfaces;
- Creating additional lift to aircraft during takeoff due to the cooling effect;
- Reducing glare on road surfaces to a great extent, particularly when wet at night;
- Reducing the interaction noise between tire and pavement;
- Eliminating or reducing the size of storm sewers; and
- Allowing air and water to reach tree roots, even with pavement within the tree drip line (Fig. 3.2).

Pervious concrete pavements' potential disadvantages and challenges include:

- Limited use in heavy vehicle traffic areas;
- Specialized construction practices;
- Extended curing time;
- Sensitivity to water content and control in fresh concrete;
- Special attention and care in design of some soil types such as expansive soils and frost susceptible ones;

- Lack of standardized test methods; and
- Special attention possibly required with high groundwater.

Engineers have specified pervious concrete in pavements as:

- Surface course;
- Permeable base and edge drains; and
- Shoulders.

The success of pervious pavement systems has been mixed. In some areas, pervious concrete pavement systems have been applied successfully, whereas in others they have clogged in a short time. Many failures can be attributed to contractor inexperience, higher compaction of soil than specified, and improper site design. For a pervious concrete pavement to work successfully:

- Permeability of soils should be verified. A percolation rate of 0.5 in./h (13 mm/h) and a soil layer of 4 ft (1.2 m) or more are generally recommended. There are installations of pervious concrete and other porous paving materials. In the red-clay Piedmont regions of the Carolinas and Georgia, however, where the subgrade infiltration rate is much less than 0.5 in./h (13 mm/h), these pavements facilitate infiltration and filtering of runoff and recharging of groundwater (although they do not infiltrate all of the rain water in large storms);
- Construction site runoff and heavy equipment should be kept from entering the pervious pavement area. The pervious concrete pavement should not be placed into service until all disturbed land that drains to it has been stabilized by vegetation. Strict erosion and sediment controls during any construction or landscaping activity are essential to prevent the system from clogging and should be incorporated into the construction site stormwater management plan; and
- Construction traffic (primarily vehicular) should be directed away from the pervious pavement area during construction to prevent compaction of underlying soil layers and loss of infiltrative capacity.

3.3.1 *Surface course*—Pervious concrete may be used as a surface course for parking lots and minor road strips (Fig. 3.1). Use in the U.S., to a large extent, has been in surface courses. Many parking lots in Florida consist of a pervious concrete surface course. Its use in Florida is due to three factors:

1. Florida frequently encounters heavy storms that cause a quick accumulation of large amounts of stormwater; the use of pervious concrete reduces the runoff volume;
2. Designers prefer the stormwater be retained on-site to recharge the groundwater system; and
3. The cost effectiveness of using pervious concrete over conventional pavements is greatly enhanced with the elimination of storm sewers.

3.3.1.1 *Parking lots*—Pervious concrete was referred to as a parking lot paving material in the central Florida area as early as the 1970s (Medico 1975). The concept developed as a means of handling the enormous quantities of water running off a parking lot during a storm; pervious concrete allows the water to percolate into the ground under the pavement. The Environmental Protection Agency (EPA) has adopted a policy that recommends the use of pervious pavements as a part of their Best Management Practices (BMPs) as a way for communities to mitigate the problem of stormwater runoff. Pervious concrete parking lots have also been selected as an integral solution to the problem of hot pavements in the Cool Communities program. The air temperature over pervious concrete parking lots is generally cooler than asphalt. Pervious concrete parking lots also reduce snow and ice buildup and are considered a nonpollutant to the environment. The practical range of design thicknesses for pervious concrete pavements is from 5 to 12 in. (125 to 300 mm) for plain parking lots.

3.3.1.2 *Roadways*—Pervious concrete for roadways is usually considered for two applications as a:

1. Drainable base, or subbase material; and
2. Roadway surface or friction course.

In both categories, although the drainage characteristics are required properties, strength requirements may vary depending on the location of the material in the pavement section. The practical range of design thicknesses for pervious concrete is from 6 to 12 in. (150 to 300 mm) for plain roadway pavements. Bonded overlays (Maynard 1970), however, have been as thin as 2 in. (50 mm). Many highways in Europe are being constructed using an overlay of latex-modified pervious concrete that allows for pavement drainage and tire-noise reduction. The latex modification results in better mechanical properties (Pindado et al. 1999).

3.3.2 *Permeable bases and edge drains*—A pervious concrete base drains water that would normally accumulate beneath a pavement. This type of construction helps to reduce pumping of subgrade materials that could lead to the failure of the pavement. In some states, the departments of transportation have created standards for constructing drainable bases and edge drains using pervious concrete. California, Illinois, Oklahoma, and Wisconsin have such standard specifications (Mathis 1990). Pervious concrete in these applications is usually lower strength (1000 psi [7 MPa] or less), and is used in conjunction with a nonwoven geotextile fabric. A similar system can be used in slope stabilization.

3.3.3 *Shoulders*—Pervious concrete shoulders have been used in France in an effort to reduce pumping beneath concrete pavements. Air-entraining admixtures are used to increase resistance to freezing and thawing. Porosities on the order of 15 to 25% have been found to nearly eliminate the risk due to freezing, unless the concrete is allowed to become saturated. Compressive strengths are often less than 2000 psi (14 MPa) at 28 days.

3.4—Other applications

3.4.1 *Drains*—Water and power resources services have used pervious concrete for the construction of permeable drain tiles as well as drains beneath hydraulic structures. The drains relieve uplift pressures and allow groundwater to be drained from beneath sewer pipes.

3.4.2 *Greenhouses*—The use of pervious concrete as a thermal storage system in greenhouse floors has been investigated by researchers (Monahan 1981; Herod 1981). The floor served as a storage area as well as a heat exchanger for the solar-heated greenhouse. Pervious concrete has also been used as paving in greenhouse floors to keep water from ponding and to eliminate the growth of weeds while providing a durable, hard surface for moving equipment.

3.4.3 *Tennis courts*—Pervious concrete has been used extensively for the construction of tennis courts in Europe. Pervious concrete slabs allow water to permeate and then drain through a gravel base to the edges of the slab. Fly ash is included in some of the mixtures to increase the workability.

3.4.4 *Noise barriers and building walls*—Noises from various traffic sources or occupants of a building can be problematic. Pervious concrete noise barriers and interior walls are sometimes constructed to reduce noise. This open-graded structure tends to absorb and dissipate the sound in the material rather than reflecting it to another location.

CHAPTER 4—MATERIALS

4.1—General

Pervious concrete, also known as no-fines, permeable, or enhanced porosity concrete (EPC), usually consists of normal portland cement, uniform-sized coarse aggregate, and water. This combination forms an agglomeration of coarse aggregates surrounded by a thin layer of hardened cement paste at their points of contact. This configuration produces interconnected voids (typically of sizes in the range of 0.04 to 0.2 in. [1 to 5 mm]) between the coarse aggregate, which allows water to permeate at a much higher rate than conventional concrete. Pervious concrete is considered a special type of highly porous concrete. Such porous concrete can be classified into two types: one where the porosity is present in the aggregate component of the mixture (lightweight aggregate concretes), and one where porosity is introduced in the nonaggregate component of the mixture (pervious concrete) (Neithalath 2004). Lightweight aggregate concrete can be constructed by using extremely porous natural or synthetic aggregates. Pervious concrete has little or no fine aggregate in the mixture. Another distinction between these two types of porous concrete is based mainly on the void structure. Lightweight aggregate concretes contain large percentages of relatively nonconnected voids. Pervious concrete, however, contains high percentages (20 to 35%) of interconnected voids, which allows for the rapid passage of water through the body of concrete.

4.2—Aggregates

Aggregate gradings used in pervious concrete are typically either single-sized coarse aggregate or grading between 3/4 and 3/8 in. (19 and 9.5 mm). Rounded and crushed aggregates, both normal and lightweight, have been used to make pervious concrete. The aggregate used should meet requirements of ASTM D448 and C33/C33M. Fine aggregate content is limited in pervious concrete mixtures because it tends to compromise the connectedness of the pore system. The addition of fine aggregate may increase compressive strengths and density but correspondingly reduce the flow rate of water through the pervious concrete mass.

Aggregate quality in pervious concrete is equally important as in conventional concrete. Flaky or elongated particles should be avoided. The narrow-graded coarse aggregate should be hard and clean, and free of coatings, such as dust or clay, or other absorbed chemicals that might detrimentally affect the paste/aggregate bond or cement hydration. Aggregate sources with a service record of acceptable performance are preferable. In the absence of a source with an acceptable service record, a combination of tests could be conducted to provide a basis for assessing the suitability of a candidate aggregate for incorporation into a pervious concrete mixture. Unit weights of aggregates should be determined in accordance with ASTM C29/C29M.

For new, unknown aggregate sources, results of tests conducted as per ASTM C33/C33M and D448 should be reviewed with the input of an experienced materials engineer. Examining untested samples by an experienced petrographer can prove to be invaluable in identifying characteristics such as quality, hardness, degree of weathering, and the presence of deleterious coatings that could impair the performance of the material in service.

Aggregate moisture at time of mixing is important. The aggregate absorption should be satisfied by conditioning the stockpile as necessary to achieve saturated surface-dry (SSD) condition. Otherwise, a dry aggregate may result in a mixture that lacks adequate workability for placing and compaction. Overly wet aggregates can contribute to draining of the paste, causing intermittent clogging of the intended void structure.

4.3—Cementitious materials

Portland cement conforming to ASTM C150/C150M, C595/C595M, or C1157/C1157M is used as the main binder. Supplementary cementitious materials such as fly ash, ground-granulated blast-furnace slag, and silica fume can also be used in addition to portland cement and should meet the requirements of ASTM C618, C989, and C1240, respectively. Testing materials in trial batching is strongly recommended to verify that cement-admixture compatibility is not a problem and that the setting time, rate of strength development, porosity, and permeability can be achieved to provide the characteristics needed for the anticipated placement and service conditions.

4.4—Water

Water quality for pervious concrete is governed by the same requirements as those for conventional concrete. Pervious concretes should be proportioned with a relatively low water-cementitious material ratio (*w*/*cm*) (typically 0.26 to 0.40) because an excess amount of water will lead to drainage of the paste and subsequent clogging of the pore system. The addition of water, therefore, has to be monitored closely in the field. Further discussion of water quality is found in ACI 301. Recycled water from concrete operations may be usable but only if it meets provisions of ASTM C94/C94M or AASHTO M-157.

4.5—Admixtures

Water-reducing admixtures should meet the requirements of ASTM C494/C494M. Water-reducing admixtures (high-range or medium-range) are used depending on the *w*/*cm*. Retarding admixtures are used to stabilize and control cement hydration. Retarding admixtures are frequently preferred when dealing with stiff mixtures, such as pervious concrete. They are especially useful in hot weather applications. Retarding admixtures can act as lubricants to help discharge concrete from a mixer and can improve handling and in-place performance characteristics. Accelerators can be used when pervious concretes are placed in cold weather. Studies report the use of cement hydration stabilizers as an aid in extending the working time of the mixture and viscosity-modifying admixtures (VMAs) to enhance workability; these advantages have also been witnessed during actual production and placements for projects. With the use of multiple admixtures in any concrete mixture, it is recommended that a trial mixture placement is conducted to identify any admixture incompatibility problems and verify desired fresh and hardened properties are consistently achievable.

Air-entraining admixtures should meet the requirements of ASTM C260. Air-entraining admixtures are not commonly used in pervious concretes, but can be used in environments susceptible to freezing and thawing. No reliable method exists, however, to quantify the entrained air volume in these materials. Research is currently underway on the resistance to freezing and thawing of pervious concrete mixtures, and most studies involve the use of an air-entraining agent (Neithalath et al. 2005a; Schaefer et al. 2006; Baas 2006). Until a greater body of research is available, it may be prudent to include an air-entraining admixture where placement occurs in colder climates. This is reportedly true in relatively higher cement content mixtures where the paste thickness coating aggregate particles exceeds 0.008 in. (200 μm). Incorporation of fibers for mixtures to be exposed to freezing and thawing has shown success in some studies to improve durability in cold climates.

The use of construction specialty chemicals is also reported to be beneficial when windy, drying ambient conditions create high evaporation rates that reduce the window of time when a mixture is most efficiently placed. The use of evaporation retarders may be helpful in this regard.

CHAPTER 5—PROPERTIES

5.1—General

The various properties of pervious concrete are primarily dependent on its porosity (air void content), which in turn depends on cementitious content, *w/cm*, compaction level, and aggregate gradation and quality. The pore sizes in the material also impact strength properties. Although pervious concrete has been used for paving for more than 20 years in the U.S., only a few investigations have been done to determine performance (Ghafoori 1995; Wanielista et al. 2007). Investigations have been based primarily on laboratory tests, with some data from actual field installations obtained. Only one ASTM method exists that is specifically intended for use on pervious concrete. ASTM Subcommittee C09.49 is developing test methods for compressive strength, flexural strength, in-place density/porosity, and in-place permeability. The specifier should use caution when referencing test methods for pervious concrete that are intended for plain concrete.

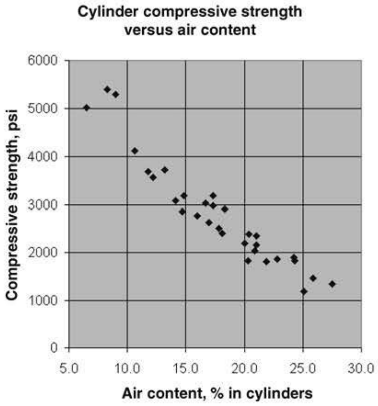


Fig. 5.1—Relationship between air content and compressive strength for pervious concrete (Meininger 1988) (1 psi = 0.006895 MPa).

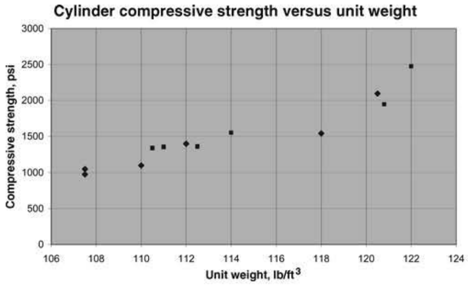


Fig. 5.2—Relationship between unit weight and compressive strength for pervious concrete (Mulligan 2005) (1 psi = 0.006895 MPa; 1 lb/ft^3 = 16.02 kg/m^3).

5.2—Compressive strength

The compressive strength of pervious concrete is strongly affected by the mixture proportion and compaction effort during placement. Figure 5.1 shows the relationship between pervious concrete compressive strength and air void content (Meininger 1988). Figure 5.1 is based on a series of laboratory tests where two sizes of coarse aggregate were used and compaction effort and aggregate gradation were varied. Figure 5.2 (Mulligan 2005) shows a relationship between pervious concrete compressive strength and unit weight. The figure is based on another series of laboratory tests where one size of coarse aggregate was used and compaction effort and the aggregate-cement ratio was varied. Figure 5.1 shows that relatively high compressive strengths of pervious concrete mixtures are possible, but the high strength is achieved only with the reduction of air void content. This results in a loss in percolating efficiency of pervious concrete. It has been reported that an 11% decrease in compressive strength was observed when the vibration

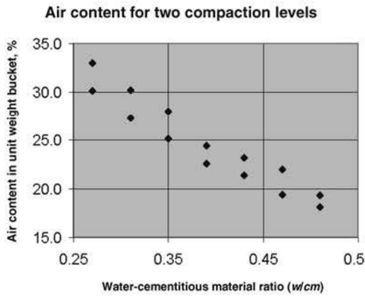


Fig. 5.3—Relationship between air content and compaction energy for pervious concrete (Meininger 1988).

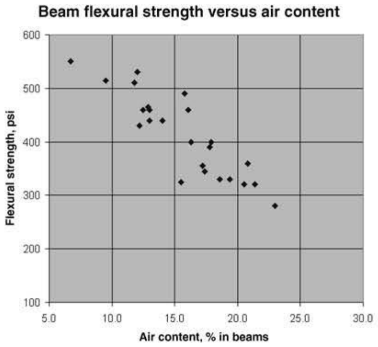


Fig. 5.4—Relationship between air content and flexural strength for pervious concrete (Meininger 1988) (1 psi = 0.006895 MPa).

amplitude of the compactor is reduced to 0.0034 in. (0.086 mm) from 0.005 in. (0.127 mm) (Suleiman et al. 2006). An increase in aggregate size has been reported to result in reduced compressive strength, while polymer additives and mineral admixtures have been found to increase the compressive strength for the same aggregate gradation (Jing and Guoliang 2003). Crouch et al. (2006) reports that an increase in fineness modulus of the aggregates reduces the compressive strength. Mahboub et al. (2008) cautions that field cored strengths can be significantly different than cast test cylinders.

Although the *w*/*cm* of a pervious concrete mixture is important for the development of compressive strength and void structure, the relationship between the *w*/*cm* and compressive strength of conventional concrete does not apply to pervious concrete properties. A high *w*/*cm* can result in the paste flowing from the aggregate, filling the void structure. A low *w*/*cm* can result in reduced adhesion between aggregate particles and placement problems. Figure 5.3 (Meininger 1988) shows the relationship between the *w*/*cm* and air void content of a pervious concrete mixture (with cement and aggregate content held constant) at two different compaction levels. Experience has shown that a *w*/*cm* of 0.26 to 0.45 provides good aggregate coating and paste stability. When fine aggregates are used in pervious concrete proportioning, the grain size of the fine aggregate in relation to the coarse aggregate is believed to influence the porosity and, consequently, the compressive strength of the material (Onstenk et al. 1993).

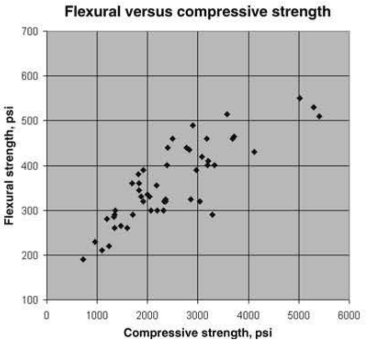


Fig. 5.5—Relationship between flexural strength and compressive strength for pervious concrete (Meininger 1988) (1 psi = 0.006895 MPa).

The total cementitious material content of a pervious concrete mixture is important for the development of compressive strength and void structure. An excessive paste content may result in a filled void structure and, consequently, reduced porosity. An insufficient cementitious content can result in reduced paste coating of the aggregate and reduced compressive strength. The optimum cementitious material content is strongly dependent on aggregate size and gradation. For the aggregate size chosen, binder drainage tests are recommended to be carried out to ascertain the optimum cementitious content (Nelson and Phillips 1994).

Another factor that can have a significant impact on the strength of pervious concretes is the thickness of the paste layer surrounding the aggregate. This is related to the aggregate size, cementitious material content, and the *w*/*cm*.

5.3—Flexural strength

Figure 5.4 (Meininger 1988) shows the relationship between pervious concrete flexural strength and air void content based on beam specimens tested in the same series of laboratory tests described for Fig. 5.1. Although these results are based on a limited number of specimens, comparing the data in Fig. 5.1 and 5.4 indicates that a relationship between the compressive and flexural strengths of pervious concrete exists. This relationship, like compressive strength, depends on several variables. Figure 5.5 (Meininger 1988) shows the relationship between compressive and flexural strengths of pervious concrete for one laboratory test series. Another series of test data relating the flexural strength and porosity is shown in Fig 5.6 (Neithalath 2004).

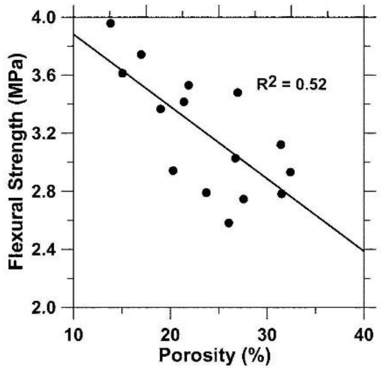


Fig. 5.6—Relationship between flexural strength and porosity for pervious concrete (1 psi = 0.006895 MPa).

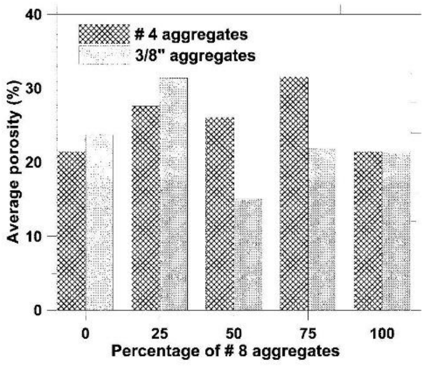


Fig. 5.7—Influence of aggregate size and gradation on the porosity of pervious concretes.

The addition of a small amount of sand (approximately 5% by volume) increases the flexural strength of pervious concrete (Neithalath 2004). An increase in flexural strength of pervious concrete has been reported when a polymer additive is used (Onstenk et al. 1993). Flexural tensile strength of about 535 psi (3 MPa) has been observed for a pervious concrete proportioned using 1/4 to 3/8 in. (6 to 10 mm) aggregates and having 25% porosity (Nissoux et al. 1993; Brite/Euram Report 1994).

Crouch et al. (2006) investigated the relationship between flexural strength f_r and compressive strength f_c' for pervious pavement. They determined that the relationship most closely matches the equation established by Ahmad and Shah (1985) for precast concrete.

$$f_r = 2.3 f_c'^{2/3} \quad \text{(in.-lb units)} \qquad (5\text{-}1)$$

$$f_r = 0.083 f_c'^{2/3} \quad \text{(SI units)}$$

5.4—Void content/density

The density of fresh pervious concrete can be determined by ASTM C1688/C1688M, and is directly related to the void content of a given mixture. Two additional methods that determine porosity of hardened pervious concrete have been reported (Neithalath 2004). The first method involves a volumetric procedure where the mass of water filling a sealed pervious concrete sample is converted into an equivalent volume of pores. In the second method, an image analysis procedure is employed on pervious concrete specimens that have been impregnated with a low-viscosity epoxy (Marolf et al. 2004). The accessible porosity in a pervious concrete mixture is a function of the aggregate sizes and relative quantities of different sizes in the mixture (Brite/Euram Report 1994). The image analysis procedure is advantageous in ascertaining the variation in porosity with depth of a pervious concrete specimen or layer.

Void content is highly dependent on several factors: aggregate gradation, cementitious material content, *w/cm*, and compactive effort.

The influence of aggregate gradation on porosity for laboratory prepared pervious concrete specimens is shown in Fig. 5.7. A range of porosities can be obtained by blending aggregates of two different sizes (Neithalath 2004). Care should be taken to ensure that the aggregate size ratio (ratio of the diameter of the larger aggregate to that of the smaller one) is not very large when using aggregate blends. If the ratio is very high (typically 2.5 or more), the smaller aggregate will fill the voids left by the larger one, reducing the porosity and, consequently, the permeability. Though the mechanical properties are enhanced using blends with large size ratios, it is generally not recommended because pervious concretes are primarily designed for water permeation.

Compactive effort has an influence on the void content, porosity, and density of a given pervious concrete mixture. In a laboratory test series (Meininger 1988), a single pervious concrete mixture compacted with eight different levels of effort, produced unit weight values that varied from 105 to 120 lb/ft^3 (1680 to 1920 kg/m^3). Figure 5.2 shows that this variation of unit weights and related air void content can have a measurable effect on the compressive strength of pervious concrete. For constant paste content, the void content is reported to be a function of compactive effort, aggregate particle shape and texture, and aggregate uniformity coefficient (Crouch et al. 2006).

5.5—Pore sizes

The sizes or size range of pores in pervious concrete is also a major factor influencing its properties. The influence of pore sizes on water permeability and acoustic absorption has been documented (Neithalath 2004; Neithalath et al. 2006). To generate larger-sized pores in the material, larger aggregate sizes are recommended. Larger-sized pores are recommended because they may reduce the chances of pore-clogging (Nelson and Phillips 1994). Figures 5.8 and 5.9 depict the influence of single-sized aggregates as well as blending two different aggregate sizes in varying proportions on the pore sizes of pervious concrete. Replacing smaller-sized aggregates with an increasing percentage of larger-sized ones increases

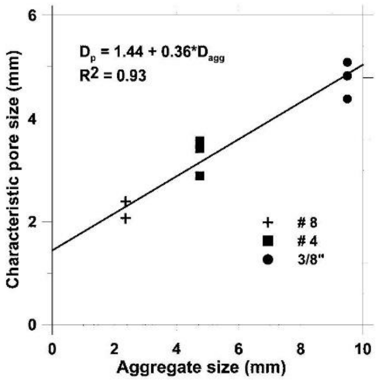


Fig. 5.8—Influence of aggregate size on the pore size of single-sized aggregate pervious concrete mixtures.

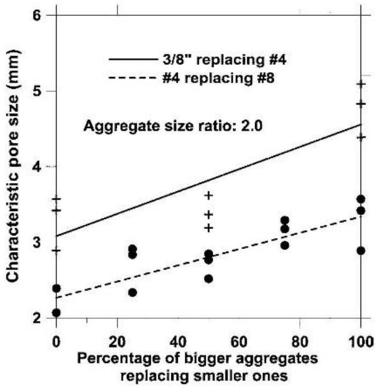


Fig. 5.9—Influence of aggregate blending on the pore size of pervious concrete.

the pore size. This is because the introduced coarser particle may not be able to fit in the void left by the removed finer particle (Neithalath 2004; Neithalath et al. 2003).

Pore structure of pervious concrete is instrumental in all the properties and performance characteristics of this material. Low et al. (2008) outlined a statistical approach to the determination of factors influencing pore structure features such as porosity and pore connectivity factor, and performance characteristic (permeability) of pervious concrete. Using a factorial design experiment with four factors (aggregate size, aggregate-cement ratio, *w/cm*, and sand-coarse aggregate ratio), 16 pervious concrete mixtures were proportioned. From a range analysis on the responses, only the first three of four factors mentioned dominate the measured responses. An image analysis method on two-dimensional sections of pervious concrete was used to characterize the pore structure. A two-parameter Weibull distribution was used to model the pore area and pore size distributions of pervious concrete.

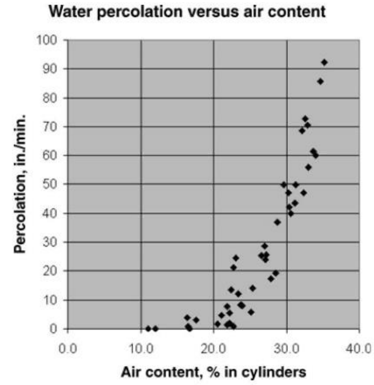


Fig. 5.10—Relationship between air content and percolation rate for pervious concrete (Meininger 1988) (1 psi = 0.06895 MPa).

The scale parameter of the Weibull distribution was used to describe the "characteristic pore area" or "characteristic pore size" of pervious concrete.

5.6—Percolation rate

One of the most important features of pervious concrete is its ability to percolate water through the matrix. The percolation rate of pervious concrete is directly related to the porosity and the pore sizes. Tests have shown (Meininger 1988) that a minimum porosity of approximately 15% is required to achieve significant percolation. For a porosity of 20 to 25%, the coefficient of permeability is reported be approximately 0.01 m/s (Brite/Euram Report 1994). Another study (Nissoux et al. 1993) reports a permeability of 0.88 gal./ft^2/s (36 L/m^2/s). Figure 5.10 (Meininger 1988) shows the relationship between the air void content and percolation rate of a pervious concrete mixture. Because the percolation rate increases as air void content increases and, consequently, compressive strength decreases, the challenge in pervious concrete mixture proportioning is achieving a balance between an acceptable percolation rate and an acceptable compressive strength.

The permeability of pervious concrete can be measured by a simple falling-head permeameter as shown in Fig. 5.11 (Neithalath et al. 2003). In this approach, the sample is enclosed in a latex membrane to avoid water flowing along the sides of the specimen. Water is added to the graduated cylinder to fill the specimen cell and the draining pipe. The specimen is preconditioned by allowing water to drain out through the pipe until the level in the graduated cylinder is the same as the top of the drain pipe. This minimizes any air pockets in the specimen and ensures that the specimen is completely saturated. With the valve closed, the graduated cylinder is filled with water. The valve is then opened, and the time in seconds t required for water to fall from an initial head h_1 to a final head h_2 is measured. The equipment is calibrated for an initial head of 11.6 in. (290 mm) and a final head of 2.8 in. (70 mm). The permeability k (in./s [mm/s]) can be expressed as

$$k = A/t$$

where A is a constant equal to 7.7 in. (192 mm).

A simple triaxial flexible-wall constant-head permeameter was also constructed for determining the permeability of pervious PCC in the range of 1 to 14,000 in./h (0.001 to 10 cm/s) (Crouch et al. 2006). Constant-head permeability appears to be a function of paste drain down, effective air void content, and void size. The results of the falling-head and constant-head methods agree reasonably for laboratory samples.

Apart from the porosity and pore size, a crucial factor that influences the permeability of pervious concrete is the pore tortuosity or the degree of connectivity of the pore network. There is no straightforward methodology to measure the pore connectivity of pervious concrete. A recent study (Neithalath et al. 2006) investigated the use of electrical impedance-based methods to determine the pore connectivity factor of pervious concretes to link it to the hydraulic characteristics of the material. It is anticipated that the widespread use of techniques like X-ray-computed tomography will lead to accurate determination of pore connectivity in pervious concretes.

The environmental benefits of pervious concrete have been well documented. Deo et al. (2008) investigated the efficiency of pervious concrete in retaining vehicular oil spills in its material structure using carefully designed experiments and modeling. Pervious concrete mixtures with porosities ranging from 13 to 25% were proportioned using two different size aggregates. The oil retention and recovery was experimentally determined on 2 in. (50 mm) slices of pervious concrete specimens using a partition gravimetric method. It was observed that a porosity of 20% is ideal for optimal oil retention in the pore structure of the material. An idealized pore-aperture model was used to develop a modeling framework for the oil retention in pervious concrete. The material parameters as well as the input features that are most likely to influence the retention and recovery of oil were identified. A genetic programming-based model was used to predict the oil retention in pervious concrete specimens. This modeling methodology provides good estimates of oil retention. The performance of the genetic programming-based model was judged in terms of its error statistics. Results obtained from this model were more reliable than those obtained using a linear regression method with the same input parameters. The study is expected to lead to further tests on optimization of pore structure of pervious concrete for applications including oil retention and water transport.

5.7—Durability

Durability of pervious concrete refers to the service life under given environmental conditions. Physical effects that adversely influence the durability of concrete include exposure to temperature extremes and chemicals such as sulfates and acids. No research has been conducted on the resistance of pervious concrete to aggressive attack by sulfate-bearing or acidic water. The durability of pervious concrete under freezing-and-thawing conditions is becoming well documented; no documented deterioration due to freezing-and-thawing cycling in the field is known to exist.

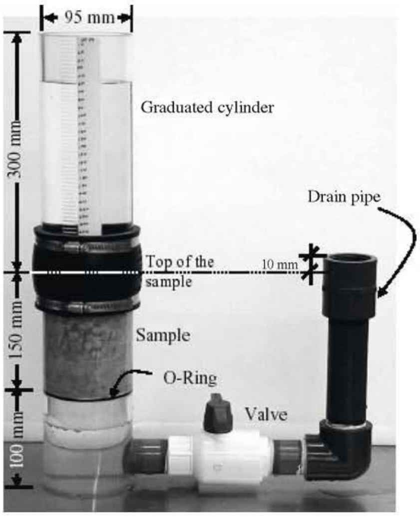


Fig. 5.11—Apparatus for measuring permeability of pervious concrete by a simple falling-head permeameter (Neithalath et al. 2003) (1 in. = 25.4 mm).

Limited testing in freezing-and-thawing conditions indicates poor durability if the entire void structure is filled with water (U.S. Bureau of Reclamation 1947). Other tests, however, have shown the pore structure being filled with water has some, but not complete, correlation with the overall results. A slower freezing condition—one cycle per day as compared with five or six as per ASTM C 666, Procedure A—may allow the water to drain from the pervious concrete, improving durability (Neithalath et al. 2005a). Limited field data exist on the long-term durability of pervious concrete in northern climates (Delatte et al. 2007); however, substantial empirical data support its use from a freezing-and-thawing resistance perspective in the Rocky Mountain and Sierra Nevada regions of the western U.S. along with other regions of the country where the standard practice is to treat conventional concrete pavements with air-entraining admixtures for the purposes of resistance to freezing and thawing. Caution should always be exercised when using pervious concrete in a situation where complete saturation before a hard freeze may occur.

Tests indicate that entraining air in the cement paste may improve resistance to freezing and thawing. In the laboratory under ASTM C666/C666M test conditions, non-air-entrained pervious concrete fails (relative dynamic modulus drops to less than 60%) in approximately 100 cycles of freezing and thawing in the chamber (ASTM C666/C666M requires a standard 300 cycles for the test). The relative

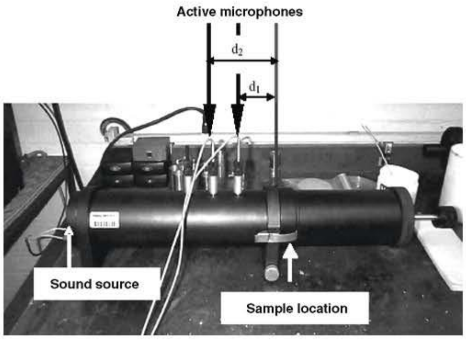


Fig. 5.12—Impedance tube for measuring the sound absorption characteristics of pervious concrete (Neithalath 2004; Marolf et al. 2004).

modulus stays well over 60%, however, for specimens that have the paste portion protected by entrained air. Also, pervious concrete specimens subjected to slow freezing and thawing (one cycle per day) suffered less damage than those subjected to the ASTM C666/C666M Procedure A test where it is subjected to five to seven cycles a day (Neithalath et al. 2005a).

Another study shows that partially saturated pervious concrete subjected to freezing and thawing in air demonstrated substantially higher durability than those subjected to freezing and thawing under water (Yang et al. 2006). Addition of small dosages of fine aggregate or synthetic fiber has been reported to increase the freezing-and-thawing resistance (Wang et al. 2006).

5.8—Toughness

Synthetic fibers can be employed to increase toughness, defined as the energy absorption of concrete after cracking. Toughness can be quantified in one of several test methods, such as ASTM C1399. This test produces a postcracking value in psi that relates to the flexural strength of the concrete matrix. Product testing of synthetic fibers in beam specimens of pervious concrete in accordance with ASTM C1399 demonstrated that fibers 1.5 to 2.0 in. (40 to 50 mm) in length were the most effective in imparting toughness to the concrete (SI Concrete Systems 2002).

5.9—Acoustic absorption

Due to the presence of a large volume of interconnected pores of considerable sizes in the material, pervious concrete is highly effective in acoustic absorption. The material can be employed as a means to reduce noise generated by tire-pavement interaction on concrete pavements. Noise reduction occurs from a combination of reduced noise generation and increased sound absorption. Pervious pavements alter the generation of noise by minimizing the air pumping between tire and road surface. In addition, pores absorb sound through internal friction between the moving air molecules and the pore walls.

To evaluate the sound absorption characteristics of pervious concrete, an impedance tube can be used as shown in Fig. 5.12 (Neithalath 2004; Marolf et al. 2004). Cylindrical specimens with a diameter of 3.75 in. (95 mm) can be accommodated in the impedance tube. The sample is placed inside a thin cylindrical Teflon sleeve, into which it fits snuggly. The sample assembly is placed against a rigid backing at one end of the impedance tube, which is equipped with a sound source. A plane acoustic wave is generated by the sound source and propagates along the tube axis. Microphones placed along the tube's length are used to detect the sound wave pressure transmitted to the sample and portion of the wave that is reflected (ASTM E1050). The pressure reflection coefficient R is the ratio of the pressure of reflected wave to that of incoming wave, at a particular frequency.

The absorption coefficient α is a measure of a material's ability to absorb sound. A material with an absorption coefficient of 1.0 indicates a purely absorbing material, whereas a material with an absorption coefficient of 0 indicates the material is purely reflective. Normal concrete, for example, typically has an absorption coefficient of 0.03 to 0.05 (Neithalath 2004). Pervious concrete typically has an absorption range from 0.1 (for poorly performing mixtures) to nearly 1 (for mixtures with optimal pore volume and sizes). Because the absorption coefficient depends on the frequency of impinging sound waves, it is important to select a proper pervious concrete thickness to minimize sounds of the desired frequency (800 to 1200 Hz is the most objectionable to the human ear).

CHAPTER 6—PERVIOUS CONCRETE MIXTURE PROPORTIONING

6.1—General

The process of developing mixture proportions for pervious concrete is often repeated trial-and-error efforts. For example, a series of trial batches may be developed in the laboratory and then tested in the field to ensure expected behavior and performance. In general, the overarching philosophy of mixture proportioning for pervious concrete is to achieve balance between voids, strength, paste content, and workability. Chapter 6 provides methods for trial batch proportioning of pervious concrete that is intended for use in pavements and other applications where drainage, percolation, or high porosity is needed. The results of the trial batch may have to be modified to better achieve the intended results in final production.

6.2—Materials

Pervious concrete is composed of cement or a combination of cement and pozzolan, coarse aggregate, and water. Although beyond the scope of Chapter 6, a small amount of fine aggregate may be incorporated to increase compressive strength. The most common gradings of coarse aggregate used in pervious concrete meet the requirements for ASTM C33/C33M aggregate sizes of 7 (1/2 in. to No. 4), 8 (3/8 in. to No. 8), 67 (3/4 in. to No. 4), and 89 (3/8 in. to No. 16).

Portland cement may conform to ASTM C150/C150M, C1157/C1157M, or any other specification that would

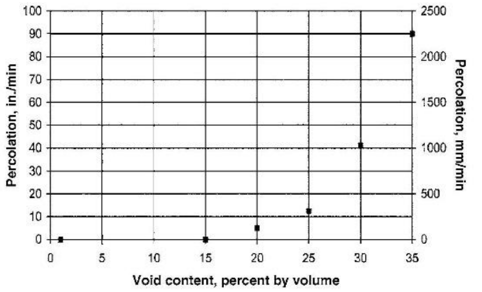


Fig. 6.1—Minimum void content for percolation on NAA-NRMCA tests and test method.

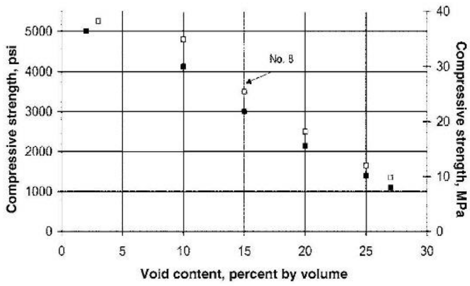


Fig. 6.2—Relationship between void content and 28-day compressive strength for No. 67 and No. 8 aggregate size.

produce an acceptable mixture. A combination of cementitious materials that each conform to the appropriate ASTM specifications can be used. Chemical admixtures are commonly used to improve various characteristics of pervious concrete. They should meet the appropriate ASTM specifications or other specifications that produce an acceptable mixture.

6.3—Water-cementitious material ratio

The water-cementitious material ratio (w/cm) is an important consideration for obtaining desired strength and void structure in pervious concrete. A high w/cm reduces the adhesion of the paste to the aggregate and causes the paste to flow and fill the voids even when lightly compacted. A low w/cm will prevent good mixing and tend to cause balling in the mixer, prevent an even distribution of cement paste, and therefore reduce the ultimate strength and durability of the concrete. Experience has shown that w/cm in the range of 0.26 to 0.45 will provide the best aggregate coating and paste stability. The conventional w/cm-versus-compressive strength relationship for normal concrete does not apply to pervious concrete. Careful control of aggregate moisture and w/cm is important to produce consistent pervious concrete.

6.4—Void content

To ensure that water will percolate through pervious concrete, the void content, both in design of the mixture and measured as the percent air by ASTM C138/C138M (the gravimetric method) should be 15% or greater, as demonstrated in Fig. 6.1.

At a void content lower than 15%, there is no significant percolation through the concrete. It is believed that below 15% voids, there is not sufficient interconnectivity between the voids to allow for rapid percolation.

Figure 6.2 shows that the higher the void content, the higher the percolation rate, and the lower the compressive strength. The lower the void content, the lower the percolation rate, and the higher the compressive strength. This figure also shows the compressive strength increases as the nominal maximum-size aggregate decreases. Compressive strength of pervious concrete is also a function of the aggregate strength, paste bonding characteristics, and strength of the cement paste itself. Some caution should be used when applying these quantitative numbers to practical design, as standardized test methods do not yet exist for these properties of pervious concrete; prior discussion should be taken as purely qualitative.

Table 6.1—Effective b/b_o values

	b/b_o	
Percent fine aggregates	ASTM C33/C33M Size No. 8	ASTM C33/C33M Size No. 67
0	0.99	0.99
10	0.93	0.93
20	0.85	0.86

6.5—Amount of coarse aggregate

Testing has shown that the dry-rodded density of coarse aggregate, as determined by ASTM C29/C29M, can be effectively used for proportioning pervious concrete (Meininger 1988). Those tests have shown that the ratio of the dry-rodded volume of coarse aggregate per solid volume of coarse aggregate b/b_o can be used as a design relationship, where

b/b_o = dry-rodded volume of coarse aggregate in a unit volume of concrete;

b = solid volume of coarse aggregate in a unit volume of concrete; and

b_o = solid volume of coarse aggregate in a unit volume of coarse aggregate.

The b/b_o value automatically compensates for the effects of different coarse aggregate particle shape, grading, and specific gravity. Furthermore, the b/b_o values for the nominal maximum-size aggregates typically used in pervious concrete, 3/8 to 3/4 in. (9.5 to 19 mm), are similar. Table 6.1 applies the b/b_o values for coarse aggregate sizes No. 8 and No. 67 with fine aggregate contents of 0, 10, and 20% of the total aggregate mass.

6.6—Paste volume, cement, and water contents

The proportioning of pervious concrete seeks to establish the minimum volume of paste necessary to bind the aggregate particles together, while maintaining the necessary void structure, strength, and workability. Figure 6.3 can be used

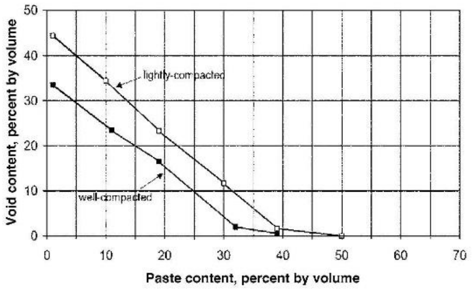


Fig. 6.3—Relationship between paste and void content for No. 8 aggregate size designations.

to estimate the volume of the paste for a mixture using normal weight No. 8 aggregates.

Once the paste volume is determined from Fig. 6.3, and the *w/cm* is selected, the cement and water quantities can be determined from the following absolute volume relationships:

paste volume V_P = cement volume + water volume

$$V_P = c/(3.15 \times 62.4\ \text{lb/ft}^3) + w/62.4\ \text{lb/ft}^3$$

Substituting $w = (w/cm)c$,

$$V_P = c/(3.15 \times 62.4\ \text{lb/ft}^3) + [(w/cm)c/62.4\ \text{lb/ft}^3]$$

c can be determined quickly by trial and error on spreadsheet or algebraically reduced to

$$c = [V_P/(0.315 + w/cm)] \times 62.4\ \text{lb/ft}^3 \qquad (6\text{-}1)$$

In SI units:

$$V_P = c/(3.15 \times 1000\ \text{kg/m}^3) + w/1000\ \text{kg/m}^3$$

Substituting $w = (w/cm)c$,

$$V_P = c/(3.15 \times 1000\ \text{kg/m}^3) + [(w/cm)c/1000\ \text{kg/m}^3]$$

c can be determined quickly by trial and error on spreadsheet or algebraically reduced to

$$c = [(V_P/(0.315 + w/cm)] \times 1000\ \text{kg/m}^3 \qquad (6\text{-}2)$$

Therefore, once the paste volume is determined from Fig. 6.3, and the *w/cm* is selected, the mass of cement can be calculated from Eq. (6-1). From the mass of cement, the water content can be computed. When fine aggregate is used, the paste volume should be reduced by 2% for each 10% fine aggregate of the total aggregate for well-compacted pervious concrete, and by 1% for each 10% fine aggregate of the total aggregate for lightly compacted pervious concrete. These reductions are necessary to maintain the same percent voids by volume.

6.7—Proportioning procedure

A procedure for producing initial trial batches for pervious concrete is shown in Section 6.7.1. The b/b_o method applies absolute volume concepts. Regardless of how the trial batch is derived, it is essential it be tested for the required fresh and hardened properties before being placed for its intended use.

6.7.1 b/b$_o$ *method*—The b/b_o method for designing a pervious concrete mixture can be broken-up into a series of eight steps:

1. Determine aggregate weight;
2. Adjust to SSD weight;
3. Determine paste volume;
4. Determine cementitious content;
5. Determine water content;
6. Determine solid volume;
7. Check void content; and
8. Iterative trial batching:
    a. Test for required properties; and
    b. Adjust mixture proportions until the required performance is achieved.

Example—Proportion a well-compacted pervious concrete mixture with a void content of at least 20%. The mixture should have a w/cm = 0.38. Use a No. 8 coarse aggregate having a dry-rodded density (unit weight) of 108.7 lb/ft^3, specific gravity of 2.75, and absorption of 1.2%. No fine aggregate will be used in the mixture.

Step 1: Determine aggregate weight

For No. 8 stone with no fine aggregate, Table 6.1 recommends b/b_o of 0.99, with dry-rodded density given as 108.7 lb/ft^3

$$W_a = 108.7\ \text{lb/ft}^3 \times 0.99 \times 27\ \text{ft}^3 = 2906\ \text{lb (dry)}$$

Step 2: Adjust to SSD weight

Given that the percentage absorbance of 1.2%

$$W_{ssd} = 2906\ \text{lb} \times 1.012 = 2941\ \text{lb (SSD)}$$

Step 3: Determine paste volume

Use Fig. 6.3 and read along the required percentage voids (20% for this example) to the well-compacted curve. Then read down to find the paste percentage at 15%. Fifteen percent of a cubic yard is 4.05 ft^3. Thus, V_P = 4.05 ft^3.

Step 4: Determine cement content

Applying Eq. (6-1),

$c = [V_P/(0.315 + w/cm)] \times 62.4\ \text{lb/ft}^3$

$c = [(4.05\ \text{lb})/(0.315 + 0.38)] \times 62.4\ \text{lb/ft}^3$

$c = 363$ lb

Step 5: Determine water content

$w = c(w/cm)$

$w = 363\ \text{lb}(0.38) = 138$ lb

Step 6: Determine solid volume

Aggregate volume $V_a = 2941/(2.75 \times 62.4) = 17.14\ \text{ft}^3$

Table 6.2—Typical[*] ranges of material proportions in pervious concrete[†]

	Proportions, lb/yd^3 (kg/m^3)
Cementitious materials	450 to 700 (270 to 415)
Aggregate	2000 to 2500 (1190 to 1480)
w/cm,[‡] by mass	0.27 to 0.34
Aggregate:cement ratio,[‡] by mass	4 to 4.5:1
Fine: coarse aggregate ratio,[§] by mass	0 to 1:1

[*] These proportions are given for information only. Successful mixture design will depend on properties of the particular materials used and should be tested in trial batches to establish proper proportions and determine expected behavior. Concrete producers may have mixture proportions for pervious concrete optimized for performance with local materials. In such instances, those proportions are preferable.

[†] Chemical admixtures, particularly retarders and hydration stabilizers, are also used commonly, at dosages recommended by the manufacturer. Use of supplementary cementitious materials, such as fly ash and slag, is common as well.

[‡] Higher ratios have been used, but significant reductions in strength and durability may result.

[§] Addition of fine aggregate will decrease the void content and increase strength.

Cement volume $V_c = 363/(3.15 \times 62.4) = 1.84\ \text{ft}^3$
Water volume $V_w = 138/62.4 = 2.21\ \text{ft}^3$
Total solid volume $V_s = V_a + V_c + V_w = 17.14 + 1.84 + 2.21 = 21.19\ \text{ft}^3$

Step 7: Determine percent voids

Percent voids = $(V_{tot} - V_s)/V_{tot} \times 100$
Percent voids = $(27.00 - 21.19)/(27.00) \times 100 = 21.52\%$

Step 8: Check estimated porosity

At 22% voids, Fig. 6.1 predicts a percolation rate of approximately 7 in./min (178 mm/min).

Step 9: Iterative trial batching and testing

The trial batch weights per cubic ft are as follows:
Cement = 362 lb
Water = 138 lb
No. 8 aggregate = 2941 lb (SSD)
Total weight = 3441 lb
Density = 3441/27 = 127.4 lb/ft^3

6.8—Typical ranges of materials

PerviousConcrete.org (http://www.perviouspavement.org/mixture%20proportioning.htm), a joint effort of National Ready Mixed Concrete Association (NRMCA) and the Portland Cement Association (PCA), has published Table 6.2.

CHAPTER 7—PERVIOUS PAVEMENT DESIGN

7.1—Introduction

In the thickness determination of a pervious pavement section, two important analyses should be conducted: one for structural adequacy and one for hydraulic characteristics. These two characteristics influence each other so they both should be addressed with care. This chapter discusses the aspects applicable to the structural design.

7.2—Structural design

7.2.1 *Subgrade and subbase*—The subbase is the aggregate layer installed below the paving. The subgrade is the soil below the paving and the subbase. The subbase provides vertical support, storage capacity, and filtering ability for treatment of pollutants. Some soils may provide adequate support and drainage so the subbase may be optional. If the support, draining abilities, or filtering abilities are limited by the subgrade, however, then a subbase material should be used. In areas exposed to freezing-and-thawing cycles, the rock subbase layer acts as insulation and provides a substantial lag in the formation of frost beneath pervious pavement (Backstrom 2000; Kevern and Schaefer 2008). The subgrade also provides vertical support for the paving. Increasing the stiffness of the subbase and subgrade increases the load capacity of a given paving system. Stiffness in the subgrade can be measured by the modulus of subgrade reaction, the California bearing ratio (CBR), or by a few other less common methods. ACI 330R provides typical stiffness values for different types of soils and provides correlations between the values calculated by the various methods.

Traditional pavement design attempts to exclude water from entering the subgrade below the pavement. In most cases, porous paving is designed to encourage water to saturate the subgrade below paving. This condition should be taken into account when determining the properties for the subgrade. The more a soil is compacted, the less porous it becomes. For this reason, pervious paving subgrades are usually compacted to a lower density than subgrades for traditional concrete paving. The level of compaction is typically 90% of Standard Proctor Maximum Dry Density (SPMDD). The modulus of subgrade reaction used in design should account for this lower level of compaction. ASTM D1883 defines a laboratory method for determining the CBR of a given soil that includes an option for soaking the soil sample in water for 96 hours before testing. This option should be used for testing fine-grained soils that would be compacted to the aforementioned 90% of the SPMDD or the compaction criteria established by the architect-engineer.

When specifying compaction for structural design, consideration should be given to the effect compaction has on the hydraulic properties of different soils. Compacting some clay soils to 90% may cause a large reduction in permeability whereas compacting sandy soils to nearly 100% may not have any affect. It is important, therefore, to carefully examine the soils present on each project for both structural and drainage capacities before specifying a compaction range. Equally important is required field testing of the subgrade and subbase for permeability after compaction to confirm they still conform to both structural and hydraulic calculations used for the site.

Expansive soils are soils that change volume when subject to changes in moisture content. Expansive soils can be mitigated by chemical treatment or by removing their upper layers and replacing them with non-expansive soil. The depth of soil replacement or soil treatment should be selected so the downward soil pressure provided by the shallow stable soil exceeds the expansive soil pressures generated by increases in the moisture content of the deeper soil. With lime stabilization, the permeability of a clayey soil is increased rapidly. Soils with higher clay contents and those compacted on the dry side of optimum tend to show greater increases in permeability with lime treatment. Some permeability, however, will decrease with age (Bell 1993). Soils treated with cement and fly ash show reduced permeability after application (Little et al. 2000). Depending on the application, reduced permeability might be desirable for applications such as water harvesting.

Some soils are subject to frost heaving. Soils located above the frost depth should be removed and replaced by soils that are not subject to frost heave. As indicted previously, an appropriate subbase has proven to be effective at protecting porous pavements from frost heaving.

Adding a granular aggregate subbase below the concrete paving increases the stiffness of the pavement support. ACI 330R, Table 3.2, indicates the increase in subgrade modulus provided by different thicknesses of subbase. This granular subbase can also be used as a reservoir for storing stormwater.

7.2.2 *Concrete strength*—Guidance for structural design of conventional concrete pavements is provided in ACI 330R for parking lots and in ACI 325.12R for streets and roads. These documents cover many different aspects of paving design. The structural design recommendations in these documents, however, are not necessarily applicable for use with pervious pavement. As there are no standardized test methods for strength of pervious concrete, design and specification by concrete strength should be avoided.

7.2.3 *Structural thickness selection*—Sufficient performance data that offer a general standard pavement design for use in prolonged exposure to heavy truck traffic is unavailable. Success of existing pavements by installers around the country varies by experience, pavement and mixture designs, and local conditions.

Traffic categories are defined by average daily truck traffic (ADTT). ACI 330R provides a full discussion of this topic. The ADTT does not correspond to a single-sized truck axle load. It assumes a collection of truck sizes from small to large, with a high frequency of small trucks and a low frequency of large trucks. Because the heaviest trucks, even in small numbers, dominate the fatigue damage of pavement, they should be the basis for traffic category selection.

Pavement designs with demonstrated performance history are available from experienced installers and being used currently in several areas of the U.S. Care should be taken to verify the installer has a history of successful performance both from installation quality and use of designs similar to any specific project needs. If unable to find suitable local installers with examples of successful projects, the National Ready Mixed Concrete Association (NRMCA) (2007) suggests pervious pavement sections of 6 in. (150 mm) of pervious concrete pavement for low (under 5) ADTT truck exposure in parking lots. This is based on historical success in the U.S. There are no current standard thicknesses for streets but there are examples of low-volume streets being installed with pavements ranging from 6 to 12 in. (150 to 300 mm) thick.

7.3—Stormwater management design

7.3.1 *General*—The major benefit of pervious concrete is its hydrological properties. From one state to another, local regulations determine how much of this benefit the designer is able to capitalize on. Even within different geological areas within a given city's limits, the regulations have been known to change. The basics of the technology are the same, however, regardless of geographic area.

Attempts have been made to reduce the impact of urbanization by reducing stormwater runoff volumes to predevelopment levels and treating stormwater before it leaves the site. In the U.S., the National Pollution Discharge Elimination System (NPDES) requires treatment of all stormwater to reduce the pollutant levels of the water. This is an empirical science, not nearly as exact as treatment of drinking water supplies due to the variability of the pollutant loads and flows. The technology is not intended to purify water to a distilled type condition because it is not practical, economical, or necessary. The intent is only to remove as much pollutant load as possible in an attempt to discharge cleaner water at sustainable rates, and reduce the impact of urbanization on water supplies.

Water supplies typically fall into two categories: surface water and groundwater. Site development on sandy soils with deep groundwater deposits may follow a design philosophy of infiltration: discharging water to the groundwater table as cleanly as possible with discharge to surface water bodies only in heavy storm events. When site development is on clayey or silty soils, or in regions of shallow bedrock, the site drainage should typically treat the water before running off site to merge with a surface water body such as a stream, river, or lake. On these low-permeability soils, however, some water infiltrates during every storm, just as it does in high-permeability soils; only the amount is less. The cumulative effect on recharge and water-quality treatment over the course of a year can be considerable.

7.3.1.1 There are three specific design features of pervious concrete that the designer may benefit from: reduced runoff volume, reduced treatment volume, and reduced impervious area on the site.

7.3.1.1.1 *Reduced runoff volume*—Reduced runoff volume is the amount of stormwater that a piece of developed property would discharge to an adjacent land or water body if stormwater BMPs were not in place; this is in excess of the predevelopment discharge volume. Such BMPs include retention ponds, detention ponds, underdrains, swales, and wetlands. Most of these BMPs consume valuable, developable real estate. By eliminating or reducing the size of these facilities, a project can be more profitable to the owner. This may reduce the amount of real estate necessary or increase the amount of rentable space.

7.3.1.1.2 *Reduced treatment volume*—Reduced treatment volume is the quantity of stormwater that should be held on site and treated before leaving the property. Treatment may occur through a combination of chemical, physical, and biological processes depending on the BMP type.

7.3.1.1.3 *Reduced impervious area*—Reduced impervious area is the fraction of the land area that does not allow infiltration of rainfall at the start of a rainfall event; this usually consists of building, sidewalk, and pavement areas. Many municipalities limit the amount of impervious area allowed on a given project site.

7.3.1.2 For a more thorough discussion of stormwater treatment BMPs, the reader is encouraged to review the information at the EPA's Web site (http:// www.epa.gov/ waterscience/stormwater). More information on local regulations can be found in the reader's regional stormwater management manual, such as the St. Johns River Water Management District's (SJRWMD) *Applicant's Handbooks: Regulation of Stormwater Management Systems* (1999). For general information on stormwater hydrology not linked to specific jurisdictions, review any of the stormwater textbooks, such as Ferguson's *Stormwater Infiltration* (1994), Ferguson's *Introduction to Stormwater: Concept, Purpose, Design* (1998), and Debo and Reese's *Municipal Stormwater Management* (2002).

The use of pervious concrete pavements as a retention or infiltration system BMP is effective for improving runoff water quality and reducing runoff volume when properly maintained (Table 7.1). The SJRWMD, for example, defines retention to include "pervious pavement with subgrade." The EPA defines pervious concrete as an infiltration system. Pervious concrete pavements can be designed to accommodate not only the rain falling on its surface, but also to capture a good portion of excess runoff from adjacent areas. To prevent premature clogging from runoff, the use of a sediment trap or other sediment separation system may be necessary. Also, calculate the increased water storage capacity requirements to hold the added storage load from the additional areas.

Reduction in drainage facilities from reduced runoff volumes using pervious concrete has an economic benefit to the developer. This economic benefit can be evaluated by comparing the price of building a pervious concrete parking lot to building a pond with drainage structures and buying the associated land.

7.3.2 *Pervious pavement maintenance*—In the past, maintenance had been a regulatory concern that prevented wide acceptance of pervious concrete. A pervious concrete pavement today will still maintain permeability even when clogged. Clogged pores or subgrade prevent stormwater from percolating through the concrete at high rates (Wanielista et al. 2007; Mata and Leming 2008). Thus, if stormwater is unable to drain through the pervious concrete layer at the design rate, it is no longer sufficiently pervious, the design benefit assumptions no longer valid, and the pavement has failed. Pervious concrete pavements can perform well for years with some level of clogging (Wanielista et al. 2007), but the rate should be above the design rate. For a pervious pavement system to perform well, it may need to be maintained at some regular interval. If a pavement is in a harsh environment, such as a coastal area, or anywhere that would cause heavy accumulations of fines, it may be necessary to perform this preventative maintenance more frequently. A qualified professional such as a licensed professional engineer or landscape architect should inspect the pavement to determine an appropriate maintenance schedule, if it is functioning properly, or if cleaning is necessary.

One nonstructural component that can help ensure proper maintenance of pervious concrete pavement is a carefully worded maintenance agreement that provides specific guidance, including how to conduct routine maintenance and surface repairs or rehabilitations. Signs should ideally be posted on the site that identifies pervious concrete pavement areas. Such signs should direct maintenance crews to the local NPDES enforcement authority and might read, "Pervious concrete pavement are used on this site to reduce pollution. Heavy vehicles prohibited. Do not resurface with nonpervious material. Call XXX-XXX-XXXX for more information."

Table 7.1—Pollutant removal of porous pavement (Winer 2000)

Pollutant	Pollutant removal, %*
TSS	95
TP	65
TN	82
NOx	NA
Metals	98 to 99
Bacteria	NA

*Data based on fewer than five data points.

Designers can account for the clogging potential of a pervious concrete pavement in their drainage design. If a site is designed for a government facility, such as a stormwater utility with an existing maintenance program and staff, clogging would not be considered. In private development where maintenance may not be performed, the designer may add a factor of safety to the stormwater design to account for the anticipated level of clogging and accompanying reduction in the porosity of the pervious concrete pavement. Some specific case studies of field performance and clogging are provided in reports by Wanielista et al. (2005) and Delatte et al. (2007). The designer of a pervious concrete pavement can reduce clogging potential by ensuring that the design of the site:

- Shows landscaped areas at lower elevations than the pervious concrete pavement (Fig. 7.1), reduces to a minimum the slope of the landscaped areas when lower elevations are not possible, and includes a curb to isolate landscaped areas that are at higher elevations than the pavement;
- Minimizes soil erosion of disturbed areas. Bare soil in these areas should be avoided and the use of permanent pasture and brush cover is recommended. Special control measures, such as silt fences, should be used at all times during construction;
- Prevents vehicles from driving from unpaved areas onto the pervious concrete pavement;
- Does not lay in the path of wind from nearby unpaved or beachfront areas; and
- Limits the amount of stormwater flowing onto the pervious concrete from adjacent, conventional (not pervious) pavements and landscaped areas unless it can be shown that:
    - ◦ The volume of water from the conventional pavement will be free of sediments;
    - ◦ The pervious subbase has been designed to handle the water from the combined areas; and
    - ◦ Sufficient pervious concrete surface area is available to catch leaves, litter, or other debris that may

Fig. 7.1—Example of landscaped area at lower elevations than pervious concrete pavement.

prematurely clog the pervious concrete between maintenance periods.

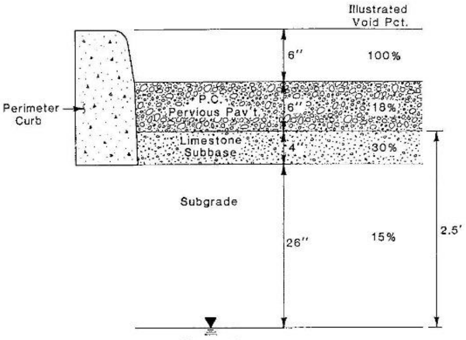


Fig. 7.2—Schematic of pervious concrete pavement designed as stormwater retention system (1 in. = 25.4 mm).

7.3.3 *Drainage design*—Runoff is estimated through the use of many accepted methods. Two of the more common tools are the rational method and the Soil Conservation Service (SCS) curve number. With either method the designer should consider in the runoff analysis a variety of input and output variables such as absorption, evaporation, rainfall intensity, infiltration, and duration of the storm. Each of these variables will have an impact on the runoff volume and the treatment volume necessary for the site.

The rational method uses a coefficient to determine the peak runoff rate for a given rainfall intensity and drainage area. The runoff coefficient *C* accounts for land use, soil type, and slope of the area. Typical values for *C* range from 0.05 for a flat lawn on a sandy soil to 0.95 for a rooftop. Other types of pervious pavements have been assigned rational coefficients ranging from 0.65 to 0.95. For a pervious pavement, the underlying soil type and its permeability will have an impact on the runoff coefficient. A well-maintained pervious pavement will typically drain faster than the subgrade soils, which limit the infiltration rate of the system. Some current research (Wimberley et al. 2001) indicates that for certain pervious concrete system designs, particularly those over well-drained subgrades and subbases, the runoff coefficient for pervious concrete is negligible for 2- to 5-year storms, and as low as 0.35 for 100-year storms. Other studies (Haselbach 2006) also indicate that there will be reduced infiltration for systems overlain with sandy soils but that the expected runoff coefficients will still be very low for most storms.

Research shows that as soil density increases, the rate of infiltration, and thus the permeability of the soil, decreases significantly (Das 1993). A decrease in the permeability of a soil would therefore justify an increase in the rational coefficient for a given design. Subgrade soils for a pervious concrete pavement should, therefore, be compacted uniformly and sufficiently to provide proper pavement support, but not overcompacted so as to reduce the permeability of the soils and increase the rational coefficient. The Florida Concrete and Products Association (FCPA) (1990) recommends compacting sandy subgrade soils to a minimum density of 92 to 96% of maximum dry density per AASHTO T-180 standards. In other parts of the U.S., for other soil types, the compaction practices are different. Glacial tills have been compacted to 90 to 95% of the standard Proctor; in the Carolinas, compaction has been to 92% of the modified Proctor; and in Georgia, fine-grained soils are commonly compacted to 95% of the standard Proctor. In this situation, it may be necessary to add an open-graded aggregate subbase (or recharge bed) to the pavement system to compensate for the softness of subgrade soil—with the benefit of added retention volume.

With the SCS method (Soil Conservation Service 1986), soils are classified into hydrologic soil groups (HSGs) to indicate the minimum rate of infiltration obtained for bare soil after prolonged wetting. The HSGs—A, B, C, and D—are one element used in determining runoff curve numbers. A-type soils have the highest permeability, with each letter designation having lower permeability in B, C, and D soils. This soil designation, in combination with the land use, will identify a curve number (CN). The CN value tells the designer which curve to reference to determine the runoff volume for a given storm event. This method is more commonly used for generating a full hydrograph rather than just estimating peak flows. Pervious concrete pavements have been assigned CNs ranging from 60 to 95. Once again, the subgrade soil type and degree of compaction have an impact on the CN and, thus, on the drainage properties of the system.

When designing a pervious pavement system, such as a retention or an infiltration system, the volume of both the pavement and subbase should be considered (Paine 1990). For example, consider a section of pervious concrete with 20% effective void space. In a 6 in. (150 mm) thick pavement section, this void space is sufficient to hold more than 1 in. (25 mm) of stormwater. Additionally, if the pervious concrete is placed on a 6 in. (150 mm) section of a crushed stone subbase, the total capacity of the system increases to approximately 2-1/2 in. (65 mm). The minimum thickness of the pervious concrete pavement will be determined by the structural needs of the pavement system. It may be necessary, however, to build a thicker pervious concrete layer or subbase layer to increase stormwater storage capacity, but this may not be the most economical solution. If further capacity is necessary, storage may be above the pavement surface in a curbed parking area (Fig. 7.2).

Other ways pervious pavements have been designed to treat stormwater include the use of an underdrain system. In this method, groundwater recharge may be limited due to site soil conditions. The pervious pavement is placed over a perforated pipe that is laid in a bed surrounded by an open-graded aggregate. Stormwater infiltrates through the pavement, through the gravel, and finds its way into the pipe. From there, the treated stormwater is discharged into a receiving water body. Treatment efficiencies for this system average 66%. Additionally, there will be some direct recharge of the groundwater that will reduce the total runoff by as much as 33%. (Florida Department of Environmental Protection [FDEP]).

Further groundwater recharge systems may include the use of drilled shafts backfilled with an open-graded aggregate, passing through clayey soils to more permeable strata. A typical design for this system might include a layer of an open-graded aggregate subbase for the pervious concrete pavement laying on the fine-grained site soils. The shafts would be spaced regularly to provide sufficient recharge capacity. The subgrade would have to be sloped to provide positive drainage to the shafts. Treatment efficiencies for this system would be expected to be similar to the underdrain design. Recharge rates, however, would be expected to be much higher.

Several other designs have been used to pass excess water-quality volume, increase storage capacity, or increase treatment volume. These include:

- Placing a perforated pipe at the top of a crushed stone reservoir to pass excess flow after the reservoir is filled;
- Providing surface detention storage in a parking lot, adjacent swale, or detention pond with suitable overflow conveyance;
- Adding a sand layer and perforated pipe beneath a recharge bed for filtration of the water-quality volume; and
- Placing an underground detention tank or vault system beneath the layers to store the treated water for reuse.

Evaporation is another important factor in the calculation of water storage. Research shows that water stored in the pervious pavement and subbase may evaporate (Wanielista et al. 2007).

All of the intricacies of a stormwater drainage design using pervious concrete pavement will be strongly tied to local practices and regulations. Refer to Section 7.3.5 for a sample set of design calculations that has been published by the FCPA (1990). Always review the full text and local stormwater regulations.

In addition to runoff, the designer should approximate pollution loads, including their nature and approximate range of concentration. This information, combined with the necessary hydrograph, will allow the designer to determine the appropriate size and design of the stormwater management system.

7.3.4 *Pervious area credit*—Many municipalities encourage green space and a reduction of runoff in development through restrictions on the amount of impervious area on the project site. Typically, impervious area is limited to 25 to 75% of a developed piece of property. Due to the nature of a pervious concrete pavement, it should not be considered impervious. With concerns over green space, however, it is rarely counted as pervious area. It is common, however, for municipalities to assign a pervious area credit for pervious concrete. Different municipalities have used values of 25%, 50%, and 100%, which to the owner means a reduction in required grassy or undeveloped area on the project site and an increase in the area that can be developed.

As an example, consider a project site that is 1 acre (43,560 ft^2 [4046 m^2]), with 10,000 ft^2 (930 m^2) of a pervious concrete parking lot. If the local municipality requires a 30% pervious area on the project site, then the site design would be limited to having 30,500 ft^2 (2800 m^2) of impervious area. This includes the building, sidewalks, and parking areas, and assumes no credit is given for the pervious concrete. With a 50% pervious area credit for the concrete parking lot, the developable area would be expanded to 35,500 ft^2 (3300 m^2)—a 16% increase in the amount of usable land on the site. This can make a project much more appealing to a developer, and with a reduction in undeveloped land, there can be a similar reduction in urban sprawl, as smaller sites could be used to fulfill specific development needs.

Local agencies are faced with the ever-growing regulations requiring stormwater treatment. It may be in their best interest to increase the percentage of credit given to pervious parking areas to the actual percent of runoff retained on-site to encourage more people to use the technology. Pervious concrete allows the city to grow with much less stress on storm drainage infrastructure. Because pervious concrete pavement allows water to flow back into dwindling aquifers, it offers a very rare opportunity to change stormwater from a liability into an asset.

7.3.5 *Design example*—Given:

- The pavement should store the first 1/2 in. (13 mm) of untreated runoff and recover that volume within a 72-hour time period following a storm.

The storage volume V_r required in the pervious pavement may be calculated as

$$V_r = \text{rainfall (in.)} \times A \text{ (acre)} \times 43{,}560 \text{ (ft}^2\text{/acre)} \times 1 \text{ (ft)/12 (in.)} \quad (\text{ft}^3) \tag{7-1}$$

$$V_r = \text{rainfall (mm)} \times A \times 1 \text{ (m)/1000 (mm)} \quad (\text{m}^3)$$

for a 1/2 in. (13 mm) first flush, then

$$V_r = 1/2\text{(in.)} \times A \times 43{,}560 \text{ (ft}^2\text{/acre)} \times 1 \text{ (ft)/12 (in.)} = 1815A \quad (\text{ft}^3)$$

$$V_r = 13 \text{ (mm)} \times A \times 1 \text{ (m)/1000 (mm)} = 0.013A \quad (\text{m}^3)$$

where V_r = volume of storage required, ft^3 (m^3); and A = size of the facility plus any contributing area, acre (m^2).

The Florida Concrete Products Association (1990) suggests that the storage capacity of a pervious pavement system on sandy subgrade soils should include the void space of the soil above the seasonal high groundwater table and any storage of the pervious concrete pavement. This storage volume may be calculated as follows

$$V_p = A \times d_1 \times p_1/100 \tag{7-2}$$

$$V_s = A \times d_2 \times p_2/100 \tag{7-3}$$

where V_p = available storage in pavement, ft^3 (m^3); V_s = available storage in subgrade, ft^3 (m^3); A = area of the pavement, acre (m^2); d_1 = thickness of the pavement, ft (m); d_2 = thickness of the subgrade, ft (m); p_1 = percentage of void space in the pavement (%); and p_2 = percentage of void space in the subgrade (%).

Upon completion of calculating the required water-quality storage volume V_r and deducting the subgrade soil volume V_s and available pavement storage volume V_p, the net difference will either be negative, indicating the requirements are met, or positive, indicating that additional storage is necessary. A granular subbase, such as an ASTM No. 57 material with a void space of 30% or greater, could provide additional storage. The area above the pavement is available for storage as well. The designer is cautioned that when applying this design technique, however, the water height for the infrequent design storm may cause the water to rise above the pavement surface. The pavement elevation should be lower than adjacent building floor elevations to avoid flood damage.

The FCPA guide (1990) gives further design examples for calculating the retention capacity of a parking area, runoff quantity, and recovery time. Some of these calculations are also given as examples in the Atlanta Regional Commission's (ARC's) *Georgia Stormwater Management Manual* (2001).

Designers may want to consider adding redundant drainage if the elevation of the finished paving surface is close to any areas that would be significantly impacted by occasional inundation. This can be as simple as grading the pavement to gently slope away from a building.

7.4—Other considerations

The properties of in-place pervious pavement are highly variable and subject to the skill and experience of the installation contractor and the concrete supplier. The concrete properties used for design should be calibrated to local experience whenever practical, but due to the specialized nature of the product and the need for qualified installers it may be advantageous to seek regional installers until qualified local installers become proficient with the product.

Pervious pavement is usually placed, then screeded and compacted. As pavement thickness is increased beyond 8 or 10 in. (200 or 250 mm), it becomes difficult to compact the full cross section of the pavement with uniform results due to a limited depth of influence of the roller. The top of the pavement will become more compacted than the bottom of the pavement. Because the strength of the pavement is increased with increased density, the design of the concrete section should consider this reduced strength at the base of the paving. At a concrete plant in Oregon, four 10 in. (250 mm) porous pavements were cut into beams to measure the difference in flexural strength between the compacted top and bottom half of the pavement. The results showed that while the top flexural strengths varied from 310 to 485 psi (2.14 to 3.34 MPa). The bottom portion of the test panels, below the effect of the compaction, had a consistent flexural strength of 272 to 275 psi (1.88 to 1.90 MPa). While this is a very limited test, it does show the noncompacted area of the pavement was consistent and that significant strength gain can be achieved by using compaction (Erickson 2006).

The void structure of a pervious concrete mixture not only allows for the vertical transmission of water, but it will also allow horizontal flow. This unique ability should be considered in establishing the drainage profiles. The vertical rate of flow is dependent on the permeability of the subgrade and on the thickness and void ratio of the pavement. To the greatest extent possible, parking area profiles should be graded without slope. This will allow increased time for the subgrade to absorb and transmit water to the lower strata and reduce the horizontal flow rate. Where conditions do not allow for flat grades, the designer may consider providing impervious barriers transverse to the direction of horizontal flow. These barriers can be installed by increasing the consolidation of the pavement strip along the edge of transverse construction joints. The increased consolidation closes the void structure at this location. Installing transverse strips of normal impervious concrete reduces lateral flow in the down-grade direction. Curbs around the perimeter of the paved area also assist in reducing lateral flow rates, as well as meeting the stormwater retention requirements. Subbase erosion and damage to the pavement can occur if insufficient steps are taken to control the volume and velocity of the water flowing through the subbase and subgrade. Edge curbs or other structures to prevent this erosion should be constructed along all areas where the potential exists for water to flow under the pavement.

CHAPTER 8—PERVIOUS PAVEMENT CONSTRUCTION

Construction of pervious concrete pavements should comply with project plans and specifications to provide a finished product that will meet the owner's needs and local regulations. A sample specification is available from ACI 522.1. Construction starts with thorough planning. A preconstruction conference and/or construction of test sections are recommended to address issues such as:

- Confirming that all project personnel are working from the latest set of plans and specifications, and all revisions are documented;
- Verifying that all required documents and submittals have been completed;
- Determining the construction sequence and joint spacing;
- Arranging the staging area for equipment, material, job-site trailers, personnel needs, and safety requirements;

- Arranging adequate access for concrete delivery trucks and concrete conveying systems;
- Selecting the optimum equipment for project size and anticipated conditions;
- Coordinating on-site inspections, and/or materials testing;
- Verifying the proposed mixture design, material and admixture availability, and proposed delivery schedule with the concrete supplier; and
- Verifying that the pervious concrete contractor, concrete plant personnel, and testing personnel (Section 9.3) are adequately qualified.

8.1—General construction principles

The characteristics of pervious concrete dictate a construction process notably different from that for normal cast-in-place concrete (Offenberg 2005a). The process is depositing, screeding, compacting, and following immediately with sheet membrane curing. Equipment that has been used successfully to place pervious concrete includes low-frequency vibrating truss screeds in combination with heavy pipe rollers, both single- and double-tube counter rotating tube screeds, plate compactors, slipforms, laser screeds, and machines specifically made for placing pervious concrete. Normal concrete finishing procedures are not employed.

No matter what equipment is used, a pervious pavement cannot be successfully constructed unless the concrete placed has the correct consistency. If too dry, a concrete creates issues with cohesiveness and cement hydration efficiency, while too wet a mixture results in the paste phase draining down, leaving a weak structure and possibly clogging the pavement bottom. Admixtures such as hydration stabilizers, viscosity modifiers, and water reducers are helpful in producing and maintaining the proper consistency of pervious concrete. The low water content and porous structure, which exposes paste surfaces to evaporation, requires that delivery and placement be completed rapidly so that sheet membrane curing can be in place within 20 minutes of concrete placement, although this time may be significantly reduced depending on environmental conditions. The porous structure also makes pervious concrete more sensitive to low temperatures during and after placement, thus dictating heightened attention to cold weather concreting practice.

8.2—Subgrade/subbase preparation

The subgrade is the bed on which the pavement structure is constructed and can be either native materials or imported fill. In some cases, pavement will be placed on a subbase of clean gravel or crushed stone, which may be used as a stormwater storage basin. If the compacted site soils or imported fill have sufficient percolation rates and the project is not in an area where freezing and thawing is a concern, then a base of gravel may not be required. The project engineer should make this determination based on local regulations, soil permeability, stormwater volume, anticipated traffic loads, and pavement purpose.

When the subgrade soil properties require that a rock base be placed below the pavement as a stormwater storage basin, nonwoven, geotextile fabric should be placed between the layer of rock and prepared subgrade. Fabric allows water to pass through, but keeps the soil in the subgrade from eroding or migrating into the voids of the subbase layer.

Well-prepared, uniformly compacted subgrade and subbase at the correct elevations are essential to the construction of quality pavement. The subgrade and subbase should not be muddy, saturated, or frozen when placement begins. In addition, the subgrade and subbase should be moistened before concrete placement begins. Failure to provide a moist support layer may result in a reduction in pavement strength and could lead to premature pavement failure. To provide a level surface for pavement construction, wheel ruts should be raked and recompacted before concrete placement begins.

8.3—Placing

A well-planned project layout can expedite construction operations, permit efficient use of placement equipment, and provide access for concrete delivery trucks. The contractor and designer should agree on joint layout and construction methods before construction begins. A drawing showing the location of all joints and the placement sequence should be available before construction begins. Locations of fixed objects should be established with the joint pattern and construction methods in mind.

Pervious concrete placement should be completed as quickly as possible. Pervious concrete has almost no excess water in the mixture. Fresh material exposed to the elements for a significant time period will lose water needed for hydration as well as retention of the cohesiveness of the mixture. This drying of cement paste can lead to loss of strength and future raveling of the pavement surface. All placement operations and equipment should be designed and selected with this in mind, and scheduled for rapid placement and immediate curing of the pavement.

8.3.1 *Forms*—Typical pervious pavement construction requires the use of edge forms, as is typical for cast-in-place slab-on-ground construction. Forms may be made of wood, plastic, or steel and should be as thick as the pavement. Forms should be of sufficient strength and stability to support equipment used for screeding and compacting during placement. The subgrade and subbase material under the forms should be compacted in accordance with the designer's recommendations. The length of the form-pins should be selected based on the type of subgrade or subbase material. Enough form-pins or stakes should be used to resist movement and bending. All forms should be cleaned and coated with the appropriate release agent as necessary.

8.3.2 *Depositing concrete*—Concrete should be deposited as close to its final position as practical. This is commonly done by direct discharge from the chute of the mixer truck directly onto the subgrade or subbase (Fig. 8.1). Generally only one section of chute can be added to the chute section mounted on the mixer truck. This limits the width of placement lanes to 15 ft (4.5 m). For placements that mixers cannot reach, or where the soil disturbance is to be minimized, a conveyor may be used (Fig. 8.2). After the concrete is deposited, it should be cut to a rough elevation with a concrete rake or similar hand tool (Fig. 8.3). Care should be

Fig. 8.1—Placement of pervious concrete by rear-discharge mixer truck.

Fig. 8.2—Use of conveyor to place pervious concrete.

Fig. 8.3—Raking pervious concrete to rough elevation.

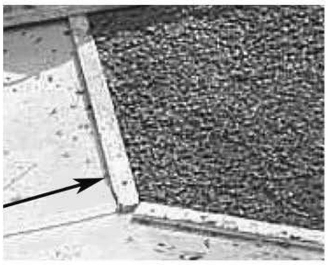


Fig. 8.4—Example of riser strip in place.

Fig. 8.5—Use of vibratory screed for strikeoff of pervious concrete.

taken to minimize filling voids in the concrete by overvibration or walking in the plastic concrete and contaminating the pervious concrete with deleterious material.

8.3.3 *Riser strips*—Pervious concrete is compacted into its final position, therefore, riser strips may be placed on top of the forms to provide an initial strikeoff elevation (Fig. 8.4). These strips vary from 3/8 to 3/4 in. (9 to 19 mm) thickness; the necessary thickness will be dependent on the required surface compaction, thickness of the pavement section, the aggregate used in the pervious concrete, and the contractor's placement methods. Refer to Section 8.4 for more details.

8.3.4 *Placing equipment*—Placement methods vary depending on the project size. For small jobs such as driveways, or for tight areas, a hand-held straightedge or vibrating screed is acceptable. For larger jobs, an A-frame, low-frequency, vibrating screed may be used (Fig. 8.5). It is important to strike off the concrete as quickly as possible. Handwork for larger placements, therefore, is not recommended due to its lack of speed. Weighted spinning-tube screeds followed by cross rolling have been used successfully to place and compact the pavement in one step, eliminating some need for riser strips. When using this process, the mixture should be properly proportioned and the concrete placed at a relatively fluid consistency to achieve adequate compaction.

There have been limited projects where laser screeds and concrete slipform equipment have been used for placing large volumes of pervious concrete in pavements. This process requires specialized expertise and experience in mixture proportioning and placement techniques. The key is that whichever method of compaction and finishing used, proper mixture consistency should be verified for the selected method.

8.3.5 *Miscellaneous tools*—Traditional concrete finishing tools such as edgers and come-alongs (a tool that looks like

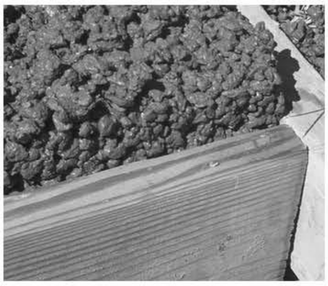


Fig. 8.6—Result of riser strip use after removal.

a hoe and has a long straight-edged blade) may be used to facilitate proper placement of pervious concrete. Bull floats and traditional concrete trowels should not be used.

8.3.6 *Using pavement as a form*—Special care should be taken when placing a pervious concrete section next to an earlier placement from the previous day. (Same-day, side-by-side placements, using mechanical equipment is not recommended). The following is the recommended procedure:

1. Carefully peel back the curing sheet covering the earlier placement to reveal just the edge of the pavement. Care should be taken to keep as much of the previous placement covered as possible. Misting of the uncovered areas is recommended;
2. Place a riser-strip or protective sheet on top of the finished placement and along the edge;
3. Place fresh pervious concrete up to the edge of the existing pavement;
4. Strikeoff the freshly placed pervious concrete to the proper elevation and compact edges, being careful not to impact the existing placement;
5. Continue with roller-finish as usual, lineup joints with previous placement; and
6. Re-cover the existing placement and the new placement with curing-sheeting.

8.4—Consolidation

When using riser-strips, they should be removed from each form immediately after strikeoff (Fig. 8.6) and the concrete be compacted to the elevation of the form with a weighted roller (Fig. 8.7). A hand-tamp may be used along the edges to facilitate compaction along the forms. The roller compacts the near-surface aggregates, resulting in a stronger bond between the surface aggregates but decreasing the permeability of the surface. The construction process should result in both adequate strength and permeability. The roller should span from form to form and be heavy enough to obtain the necessary compaction. The average roller of the size needed to span a 12 ft (3.7 m) lane width weighs approximately 500 lb (227 kg). A custom-built rolling tool (Fig. 8.8) can be used in tight areas and for smaller placements. The roller in Fig. 8.8 weighs approximately 70 lb (32 kg). To decrease the chance of leaving roller-marks in the surface of the pavement, small rollers should have machined beveled-edges.

Fig. 8.7—Example of compaction of pervious concrete by rolling.

Fig. 8.8—Example of small roller used for compacting small paved area.

Extra compaction may be necessary in some areas such as tight turn-radiuses of the parking lot pavements. Because these areas may receive more wear from increased stresses as a result of the turning motion of passing vehicles, it is recommended these areas receive a greater surface compaction, even at the loss of some surface permeability, by using a thicker riser-strip in the radius areas

Some situations require extra effort to ensure a quality pavement. Where ride quality is of special concern, as in drive-lanes, the pavement may be cross-rolled to smooth out vertical deviations (Fig. 8.9). Adjacent to sidewalks and at exposed pavement edges, the concrete may be tooled to provide a smoother and tighter corner (Fig. 8.10). This operation performed at the wrong time could result in cracking of the matrix and thus increased raveling. Great care should be taken when performing this operation. After strikeoff, compaction, and edging, no other finishing operations should be performed.

8.5—Jointing

Contraction joints, sometimes referred to as control joints, should be installed as indicated by the plans. They should have a depth of 1/3 to 1/4 of the thickness of the pavement. Although it is highly recommended that joints be installed in the fresh concrete with special tools, saw cutting joints after the concrete hardens can also be performed. Shrinkage cracks will occur in pervious concrete as well as in conventional

Fig. 8.9—Secondary roller used for cross-rolling pervious concrete to improve the ride quality of pavement.

Fig. 8.10—Edging pervious concrete to improve appearance of corners.

Fig. 8.11—Detailed view of jointing tool for pervious concrete.

Fig. 8.12—Example of jointing tool built into primary roller.

Fig. 8.13—Demonstration of curing with plastic sheeting immediately after compaction

concrete, and can occur in large placements even before the concrete has had time to cure enough for saw cutting. Conventional concrete jointing tools may be used for small placements such as sidewalks. A specially designed compacting roller-jointer with a blade that is at least 1/4 the thickness of the slab, and with enough mass to force the blade to cleanly cut the joint, is the tool of choice (Fig. 8.11). In placements with wide lane widths, a longitudinal joint may be cut with the compacting roller (Fig. 8.12). In all types of roller-jointers, the junction of the blade and roller should incorporate a small concave-radius to reduce the square-edges at the top of the joint. Square edges have a greater tendency to ravel under traffic loading.

If the contraction joints are saw-cut, the procedure should begin as soon as the pavement has hardened sufficiently to prevent damage to the surface. Only enough polyethylene cover material to saw cut the required areas should be removed (Fig. 8.13). After sawing, the exposed areas should be soaked with water, which flushes the pores of the fines generated by sawing and ensure that sufficient water is present for proper curing. Immediately re-cover the exposed area with a polyethylene covering sheet as soon as saw cuts have been made.

8.6—Curing and protection

The open pore structure of pervious concrete makes curing particularly important because of the larger surface area exposed to drying (dehydration). Immediate curing of pervious concrete is vital for performance. Under favorable conditions of high humidity and low wind velocity, the cover material should be placed no later than 20 minutes following discharge. Under more severe environmental conditions the cover material should be placed sooner. The cover material should be heavy-duty polyethylene sheet, meeting the requirements of ASTM C171, of sufficient dimension to cover the entire width of a lane (Fig. 8.13). Woven materials

Fig. 8.14—Example of use of reinforcing bars to hold down curing material.

such as burlap and geotextile fabric should not be used as they will not hold the moisture in the concrete. Spray-applied curing compounds do not produce acceptable results.

Strikeoff, compaction, and curing operations should be kept as close together as possible to prevent the top surface of the pervious concrete from drying. Following the placement process, as soon as the strikeoff operation has moved on to a new riser strip, the used riser strips should be removed and the compaction operations begun. When adverse ambient weather conditions exist, such as high temperature, high wind, or low humidity, an evaporation reducer may be lightly sprayed on the surface following strikeoff operations and before compaction. Before covering, if the concrete has lost its sheen, it should be lightly misted with water but never sprayed.

The polyethylene cover should completely cover all exposed surfaces and should be secured in place outside all pavement edges and at laps to prevent evaporation from the concrete and being displaced by wind (Fig. 8.14). Reinforcing bars, lumber, or concrete blocks may be used to secure the polyethylene cover to prevent it from being blown off. Dirt, sand, or other granular material should not be placed on top of the polyethylene cover, as they may wash into the pores of the concrete during a heavy rainfall, or during removal of the cover. If wooden forms are used, the riser strips may be used to secure the sheets in place. The sheets should first be attached to the top of the form on one side of the lane by reattaching the riser strips to the top of forms with button-cap nails, with the polyethylene sheet sandwiched between the form and riser strip. The sheet should then be pulled as tight as possible to eliminate creases and minimize the possibility of discoloration or striping of the concrete. All surfaces of the pavement should be covered properly. Not doing so may result in raveling of the exposed areas. Any loss of moisture, such as from wind getting under secured plastic, can be detrimental to the proper curing and strength development of the pavement.

The owner should be made aware of possible discoloration of the pavement surface due to the differential curing under the plastic sheeting. Over time the discoloration should even out to a single gray color.

For proper curing, the pavement should typically remain covered for at least 7 days for plain cement concrete mixtures, and 10 days for concrete mixtures that incorporate supplementary cementitious materials such as fly ash or slag. It may be necessary in cold weather to increase these typical curing times. Striping should be applied only after the curing period has passed (Fig. 8.15). No traffic should be allowed on the pavement during curing. The general contractor should take measures to prevent damage to the pavement due to abuse from construction operations. Specifically, the general contractor should prohibit removal of the curing material and prevent any traffic on the pervious concrete pavement. Additionally, the general contractor should not allow storage of building and landscaping materials on the pavement surface as these materials can clog the pores or otherwise damage pervious pavements.

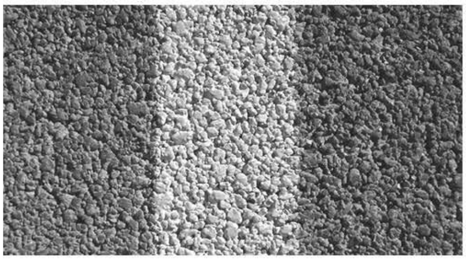


Fig. 8.15—Painted lines visible on pervious concrete pavements.

8.7—Cold weather protection

Pervious concrete is more sensitive to cold weather than normal concrete (Section 8.1) and, therefore, pervious concrete construction may be suspended or curing blankets used when ambient temperature during, and one day after, placement is expected to fall below 40°F (4°C). Due to rapid evaporation causing insufficient water for cement hydration, hot water should not be used in batching pervious concrete. During curing, measures should be taken to protect the pervious concrete from freezing while maintaining moisture for the time necessary to achieve the desired strength. Curing blankets work sufficiently to serve this purpose.

8.8—Hot weather protection

In hot weather, transporting, placing, and compacting should be done as quickly as possible. An evaporation retardant may be applied to the surface of the concrete following the strikeoff process to retard the loss of moisture on the surface. After consolidation and before placing the polyethylene, the surface may be lightly misted with water or an evaporation retardant if the surface appears to be losing its sheen appearance.

8.9—Repairing pervious concrete pavements

8.9.1 *Grinding*—High spots can be ground with a weighted grinder; however, the grinder will cut through and expose the aggregate in ground areas, changing the appearance of the pavement.

Table 8.1—Typical maintenance activities for pervious concrete placement

Activity	Schedule
• Ensure that paving area is clean of debris • Ensure that the area is clean of sediments	Monthly
• Seed bare upland areas • Vacuum sweep to keep the surface free of sediment	As needed
• Inspect the surface for deterioration or spalling	Annually

8.9.2 *Holes or low spots*—Small holes (low spots) should be patched with an aggregate/epoxy blend or latex-modified cement. To match the appearance of the pavement surface, the aggregate may be coated with wet cement and cured before patching. Large holes should be patched with pervious concrete of the same mixture proportions as the original surface. When patching, it is highly unlikely that the color of the patch will match the original surface material. Epoxy bonding agents or latex-modified cement may be used to ensure proper bonding between the old and new surfaces. Acrylic paints have been used to disguise the area of the patch with varied success. Unbonded thin sections of patch material may not remain intact under traffic loading. If in doubt, a full-depth repair is recommended.

8.9.3 *Utility cuts*—In the event that a section of pervious concrete is cut, a full-depth repair should be performed. This would include removing a square section the width of a placed lane such that the new material would be large enough to maintain its structural integrity under loading.

8.10—Maintenance

Pervious concrete pavements are infiltration-based systems. Water passing through the pavement will carry with it varying degrees of soluble and insoluble pollutants and trash. Most of this debris will be deposited on or near the pavement surface. Maintenance of pervious concrete pavements consists primarily of removing the accumulated debris. Two commonly accepted maintenance methods are pressure washing and power vacuuming. Pressure washing may force some of the debris down through the pavement surface. This is effective, but care should be taken not to use too much pressure, as this will damage the pervious concrete. A small section of the pavement should be pressure washed using varying water pressures to determine the appropriate pressure for the given pavement. Power vacuuming removes contaminants and debris by extracting them from the pavement voids. The most effective scheme, however, is to combine the two techniques and power vacuum after pressure washing. A suggested maintenance schedule is found in Table 8.1.

Research conducted by the FCPA (1990) quantifies the extent of contaminant infiltration in pervious concrete parking lot pavements. Five parking lots were examined as part of the study, and the level of contaminant infiltration was found to be quite low. Infiltration was found to be in the range of 0.16 to 3.4% of the total void volume after up to 8 years of service, and brooming the surface immediately restored over 50% of the permeability of a clogged pavement.

CHAPTER 9—QUALITY CONTROL INSPECTION AND TESTING

9.1—General

As with any engineered material, it is important to verify the quality of a pervious concrete pavement. Tests performed of the subgrade condition are to ensure adequate density, support value, and permeability. Testing of the pervious concrete mixture should be conducted for both the fresh and hardened properties of the concrete for quality assurance of density and thickness. Many of the present ASTM and AASHTO testing methods are applicable to a pervious concrete pavement installation. Due to the physical characteristics of the material, however, not all traditional concrete tests are appropriate for pervious concrete.

Due to the lack of test methods for this material, ASTM Subcommittee C09.49 is developing test methods specifically for pervious concrete. As of 2008, five test standards were in development, including: Fresh Density and Void Content, Compressive Strength, Flexural Strength, Field Permeability, and Hardened Density and Porosity.

9.2—Preconstruction inspection and testing

Determining the permeability of the subgrade and soil analysis is particularly important in the design and construction of the pervious concrete system. Basic tests of the properties of the subgrade should include a particle size analysis (ASTM D422), soil testing and classification (ASTM D2487), and standard or modified proctor test (ASTM D698 or ASTM D1557). The results of these tests will provide the designer with the necessary data.

The standard percolation test used for designing septic fields is not an appropriate test for determining subgrade permeability for pervious pavements. A test section of the subgrade should be compacted to the specified density as part of the soil analysis before completion of the project design. A double-ring infiltrometer (ASTM D3385) or other suitable test should be performed to adequately test the permeability. For small projects, these tests may not be necessary, especially if the designer has previous experience with similar local soils.

Normal soil testing procedures for subgrade density (compaction) in accordance with a standard ASTM test procedure should be performed before concrete placement as part of a normal quality-control plan.

9.3—Inspection and testing during construction

As described in ACI 522.1, acceptance criteria should have two distinct aspects. The first criterion should be based on the pervious concrete mixture as delivered and is based on the density. For each day's placement, or when visual inspection indicates a change in appearance of the fresh mixture, at least one test should be conducted to verify the density of the material. The test of the mixture should be conducted in accordance with ASTM C1688/C1688M. Acceptance should be based on ±5 lb/ft^3 (80 kg/m^3) of the specified fresh density. The second acceptance criterion should be based on the completed pavement as outlined in the following section. Field tests and inspections of pervious concrete should be performed by an individual certified as

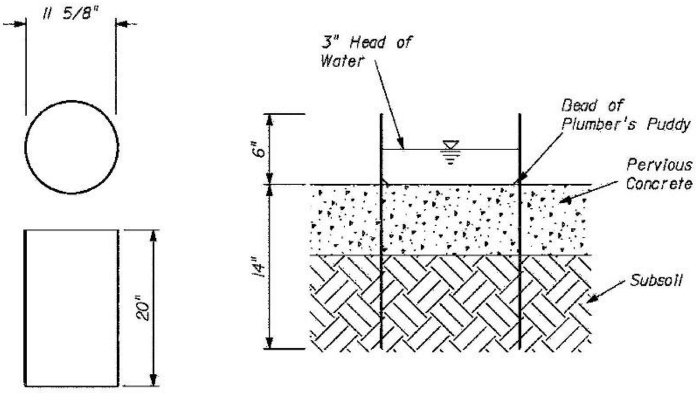


Fig. 9.1—Single-ring infiltrometer (1 in. = 25.4 mm).

both an NRMCA Certified Pervious Concrete Technician or equivalent and an ACI Concrete Field Testing Technician—Grade I or equivalent.

9.4—Postconstruction inspection and testing

The hardened density of a properly placed pervious pavement should not vary substantially from the fresh density of the mixture. Coring of three samples of the pavement will result in acceptance samples for thickness and density and should be tested for each lot of 5000 ft^2 (465 m^2) of pavement placed. Core samples should be obtained in accordance with ASTM C42/C42M not less than 7 days after placement. The cores should be measured for thickness by an ACI certified Laboratory Technician according to ASTM C42/C42M and tested for density according to ASTM C140 (ASTM Subcommittee C09.49 is developing methods specifically for Pervious Concrete.). The placement thickness should be determined using untrimmed, hardened core samples. After thickness determination, the cores should be trimmed and measured for unit weight in the saturated condition as described in Paragraph 9.3, Saturation, of ASTM C140.

After immersing the trimmed cores in water for 24 hours, drain for 1 minute, remove surface water with a damp cloth, and then weigh immediately. Tolerance for thickness reported as the average of three cores of each lot should not be more than 1/4 in. (6 mm) less than the specified thickness, with no single core exceeding 1/2 in. (13 mm) less than the specified thickness, nor should the average compacted thickness be more than 1.5 in. (40 mm) more than the specified thickness. The acceptable hardened density should be within ±5% of the approved hardened density from the test panels.

In addition, visual inspection of the cores will allow for verification of the necessary open void space to facilitate drainage. A visual inspection that shows a fully closed or severely restricted pore structure may indicate a pavement that will not function properly, and those sections demonstrated to be essentially impervious should be removed and replaced. Agreement as to what is essentially impervious and the method of measurement should be achieved before initial placement.

Tests are being developed for determining the in-place permeability of pavements. One of the recent test methods that have been developed is the embedded single-ring infiltrometer (Fig. 9.1) to determine the infiltration rates of the pervious concrete system (Wanielista et al. 2005). This can be used either as a preconstruction tool or a postconstruction tool. The single-ring infiltrometer uses the same testing procedure as the double ring, as outlined in ASTM D3385 with the modification of its embedment and the use of a single ring. It is postulated that this is a valid modification to test the infiltration rates of the entire system and avoid a lateral migration of water in the pavement alone. The depth of penetration is an important variable and will be refined based on results from extensive field testing.

At no time should acceptance be based on the compressive strength of the pervious concrete, either as delivered or as cored from the pavement. Due to the relationship between compaction and compressive strength, there is a wide range of strengths that can be generated from a single delivery of pervious concrete. Additionally, there are no standard test methods for testing the compressive strength of pervious concrete. Typical coring procedures, when used on pervious concrete, disturb the cement paste matrix such that compressive strength testing results may be inaccurately low. Local experience with materials through completed projects, test panels, or both should give an indication whether a specific mixture proportion will have sufficient strength to withstand the stresses of the design traffic loads.

CHAPTER 10—PERFORMANCE

10.1—General

Pervious concrete pavements more than 30 years old are still in service. Information from controlled studies is available concerning the long-term performance of pervious concrete pavements. The performance parameters discussed in Chapter 10 include changes in infiltration rates, structural distress, surface distress, and resistance to freezing and thawing.

10.2—Changes in infiltration rates

Clogging occurs when foreign materials restrict the ability of water to flow through the pervious concrete pavements. These foreign materials can be fines that enter the pervious concrete matrix or vegetative matter that collects on the surface or in the pores of the pervious concrete. Fines are water-borne, wind-borne, or tracked onto the pervious concrete pavement by traffic. Vegetative matter comes from trees or plants adjacent to the pervious concrete pavement.

Water-borne fines come from stormwater runoff that starts outside the limits of the pervious concrete pavement and transports material onto the pavement. A geometric design of the pervious concrete pavement that does not allow stormwater or traffic to introduce fines onto the pavement will minimize clogging. For example, pervious concrete pavements should be placed at elevations above adjacent landscaping, with the landscaping sloping away from the pavement. Wind-borne fines are generally of limited volume in many areas, but could be of concern in arid areas. Vegetative matter will routinely be deposited onto the surface of pervious concrete pavements, requiring periodic cleaning. Construction operations adjacent to pervious concrete pavement may also cause fines to be deposited. Construction, therefore, should be sequenced to avoid deposition of these fines.

A field-performance investigation was conducted in Florida in 1989 on pervious concrete pavements up to 13 years old (Wingerter and Paine 1989). The study concluded that properly designed, constructed, and maintained pervious concrete pavements showed only small amounts of clogging after many years of service. The study also included the percolation rate measurement on clogged pervious concrete pavement. The percolation rate of the clogged pervious concrete pavement was still equal to adjacent grass. A more recent investigation of several field sites in Florida and other southeast U.S. locations has been carried out (Wanielista et al. 2007). This study indicated that pervious concrete pavements that were installed 10 to 15 years ago, with no maintenance requirements, are operating in a satisfactory manner with insignificant amounts of clogging. This study also looked at potential rejuvenation methods in case clogging occurred, which included pressure washing and/or vacuum sweeping of the pavement. It also concluded that the most important criteria for continued satisfactory performance of these pavements were proper design and installation.

10.3—Structural distress

Structural distress in pervious concrete pavements generally takes two forms: cracking or subsidence due to loss of subgrade support. Structural distress can be caused by heavy loads (beyond the structural capacity of the pavement), weak subgrade materials, or horizontal water flow through the pervious concrete paving that washes away subgrade material. High surface contact pressures or a weak pervious concrete surface can cause surface raveling.

10.4—Surface distress

Surface distress is the removal of loose aggregate material from the pervious pavement surface. A field performance investigation carried out in Florida (Wingerter and Paine 1989) indicated that pervious concrete pavements with surface raveling were caused by an inadequate *w/cm*, inadequate compaction, or improper curing procedures. The investigators reported that the pervious concrete pavement projects had no signs of structural distress. Once a top layer of loose surface material has been removed, the raveling often stops. A modified version of an abrasion test to assess a mixture's resistance to surface distress has been developed (Offenberg and Davy 2008).

10.5—Resistance to freezing and thawing

The void structure of pervious concrete is not the same as the entrained air in regular portland-cement concrete. In properly designed and installed pervious concrete pavements, water drains through it to an underlying drainage layer and soil, and will not be retained in its void structure. When the pervious concrete is completely saturated and subjected to freezing, however, the water has no place to drain. This can result in excessive stresses on the thin cement paste coating the aggregates, and may cause deterioration of pervious concrete installations. Some fully saturated non-air-entrained pervious concrete had poor freezing-and-thawing resistance when tested in the laboratory according to Procedure A of ASTM C666/C666M (Neithalath et al. 2005a). It is possible to add air-entraining admixture to pervious concrete mixtures to protect the coating paste, but the entrainment of air cannot be verified or quantified by current standard test methods. Pervious concrete that is partially saturated could possibly have sufficient voids for water movement, demonstrating good freezing-and-thawing resistance.

ASTM C666/C666M is used to test fully saturated concrete samples. This does not simulate the performance of pervious pavement in the field because properly built installations in freezing-and-thawing environments contain a mechanism for draining water out of the pavement. Currently, there is no standard method for evaluating the resistance to freezing and thawing of pervious concrete. The important factor is its ability to drain any water entering its structure in the anticipated weather conditions.

National Concrete Pavement Technology Center (Schaefer et al. 2006) tested several different mixture designs for resistance to freezing and thawing. They determined that saturated samples made according to one mixture design only had a 2% mass loss when subjected to 300 freezing-and-thawing cycles in accordance with ASTM C666/C666M Method A. This mixture incorporated No. 4 aggregate, 7% sand, 571 pounds of cement per cubic yard (338 kg/m^3), and a 0.27 *w/cm*. This mixture used both air entrainment and high-range water-reducing admixtures. Samples made according to this mixture had a void content of 18.3%. They determined that the addition of binder latex to the mixture helped with resistance to freezing and thawing, but not to the same extent as adding a small amount of sand to the mixture.

These precautions are recommended to enhance the freezing-and-thawing resistance of pervious concrete:

- Use an 8 to 24 in. (200 to 600 mm) thick layer of clean aggregate base below the pervious concrete;

- Attempt to protect the paste by incorporating air-entraining admixture in the pervious mixture. Limited and preliminary lab testing shows that fully saturated air-entrained pervious concrete had significantly better freezing-and-thawing resistance when tested under ASTM C666/C666M;
- Place perforated PVC pipe in the aggregate base if the aggregate subbase is not thick enough to drain water through the paving, to capture the water and let it drain away below the pavement; and
- Consider adding a small amount of sand to the concrete mixture.

Not every situation warrants all of these safeguards. The safeguards are organized in the order of preference. For example, a pervious concrete sidewalk at Pennsylvania State University in University Park, PA, which is a hard, wet-freeze area, has shown good performance over five winters and has only an 8 in. (200 mm) thick layer of aggregate base underneath the pervious concrete. There are many pervious concrete projects in Georgia, Pennsylvania, Tennessee, North Carolina, and New Mexico subject to various freezing-and-thawing conditions that are performing admirably (NRMCA 2004, 2007). Baas (2006) surveyed individuals across the country and asked them to describe their observations of pervious concrete freezing-and-thawing resistance. Respondents in Ohio, Minnesota, Northern Kentucky, Tennessee, Indiana, and California did not report any freezing-and-thawing deterioration of pervious pavement installations. Pervious concrete installations in the heavy snow areas of Colorado, Utah, Vermont, New Hampshire, Nevada, Montana, and Northern Arizona have also shown no signs of deterioration due to freezing-and-thawing cycling. The same can be said for the Maritime Provinces of Eastern Canada where a number of pervious concrete installations have also taken place and where air-entrained conventional concrete is typically specified. Field performance was investigated for approximately two dozen pervious concrete sites located in the states of Ohio, Kentucky, Indiana, Colorado, and Pennsylvania. Generally, the installations evaluated had performed well in freezing-and-thawing environments, with little maintenance required. They were, however, relatively new, so there is a need to follow up later on field performance (Delatte et al. 2007).

Pervious concrete is historically not recommended in freezing-and-thawing environments where the groundwater table rises to a level less than 3 ft (0.9 m) from the top of the surface of the subgrade. New details, however, have been developed for using pervious concrete on sites with high groundwater tables and poorly draining soils (Ohio Concrete Ready Mixed Association) (http://www.ohioconcrete.org).

CHAPTER 11—LIMITATIONS, POTENTIAL APPLICATIONS, AND RESEARCH NEEDS

11.1—Pervious concrete in cold climates

The most widespread applications of pervious concrete include paving and surface treatments to permit drainage. These can take many forms, such as parking lot surfaces, roads, storage, and liquid/solid separation operations such as in agricultural manure dewatering. Each use has different limitations and concerns. Further research would help to extend its use in these and in other applications and to verify its performance in various environments.

Some areas of research needs are as follows:

- Strength determination and limitations;
- Characterization of material structure;
- Freezing-and-thawing and cold climate applications;
- Porous grout and other pore pressure reduction potentials;
- Stormwater management;
- Environmental filtering/remediation potential;
- Surface deterioration and repair;
- Development and standardization of broader testing methods;
- Nondestructive test methods for performance evaluation and prediction;
- Urban heat island effect, carbonation, and other thermal properties; and
- Other novel applications.

11.2—Strength determinations and limitations

Further research is needed to understand and improve the strength of pervious concrete. The ability of pervious concrete to withstand heavy vehicular loads (typical delivery truck or highway traffic) would enhance its use in a wide range of applications. There has been some research into the compressive and flexural strengths of some pervious concretes (Yang and Jiang 2003; Neithalath 2004; Marolf et al. 2004; Wimberley et al. 2001; Crouch et al. 2003; Zouaghi et al. 2000). Delatte et al. (2007) measured the porosity and strength of several cores removed from in-service pervious concrete pavements. There are many different variations and applications; however, for pervious concrete, the strength is dependent on porosity (Neithalath 2004; Marolf et al. 2004; Mulligan 2005; Montes and Haselbach 2006). ASTM C39/C39M has therefore not proven to be an effective means of measuring compressive strength. Placement techniques can also develop vertical porosity distributions in the pervious pavement, which may have impacts on the flexural strength and other characteristics (Haselbach and Freeman 2006). Additional research is needed to confirm that applicable 28-day strengths can be reliably achieved in production applications and into the various applications and strength characteristics of pervious concrete.

While pervious concrete is used more often for stormwater management in the U.S., interest in pervious concrete in other parts of the world has focused on wearing course applications. Europe, Japan, and Australia have investigated pervious concrete for roadway use for noise reduction (Neithalath 2004) and improved skid resistance during rain events (Wang et al. 2008). Pervious concrete in these cases is placed using either the wet-on-wet method, where pervious concrete is placed overtop of fresh conventional concrete, or as a surface to precast concrete panels. The quietest pavement in the world is a section of roadway in the Netherlands comprised of precast concrete sections containing a pervious concrete wearing course. There is concern about using pervious concrete for road surfaces where traditional impervious designs avoid water seepage into the subbase, as this may undermine the subbase and, therefore, lose critical structural support under the impervious pavements. Much of this loss of material in the subbase, however, is due to hydrostatic forces in this area of water seepage that occur from point loads from vehicle wheels on the surface that push the soils away. Pervious concrete would of course allow for water seepage into the subbase, as water infiltration is its intention. This may not, however, have the same destructive hydrostatic forces on the subbase, as the water could also move vertically in the pervious column. Research into the water impacts on strength and the underlying soils for additional applications of pervious concrete as road surfaces is needed.

More research is also needed into the fatigue performance of pervious concrete under load because that influences pavement design. Preliminary research shows that pervious concrete has the same fatigue performance as plain concrete, but that work needs to be expanded (Tamai et al. 2004).

11.3—Characterization of the material structure

The properties and performance of any porous material depends extensively on its pore structure features such as the total pore volume, pore sizes and their distribution, and the connectivity and tortuosity of the pore structure. Because pervious concrete is primarily used for stormwater management, the functional performance characteristic that is more often a concern for the end user is the permeability. Porosity is considered as the most important feature of the pore structure of porous materials, but it alone is insufficient in providing a complete description of the material performance. A higher porosity does not necessarily ensure higher permeability because the permeability is a function of the pore surface area, pore sizes, and tortuosity. Using aggregates of different sizes in pervious concrete to produce the same porosity has resulted in different permeability values (Neithalath et al. 2006); a proper understanding of the pore structure features and how it is influenced by the material parameters and mixture proportioning needs careful and thorough investigation. A few studies have reported the influence of aggregate gradation and blending on the porosity, pore sizes, and connectivity of pervious concretes (Neithalath 2004; Neithalath et al. 2006; Low et al. 2008) using mathematical and statistical procedures. To develop performance-based material design for pervious concretes, significant research is needed in understanding the pore structure of this material. The macroporosity of pervious concretes can often lead to crack arrest effects if the porosity and pore sizes are conducive. This influences the structural performance of the material. A comprehensive understanding of material performance and a material design-based mixture proportioning, therefore, can be accomplished only if the pore structure characteristics are well understood.

11.4—Freezing-and-thawing and cold climate applications

More research would be valuable to evaluate the efficacy of known technologies in protecting pervious concrete in cold climates. Although there have been many pervious concrete pavements installed in colder areas, several questions remain to be conclusively answered so that pervious concrete can be used with greater confidence and for broader application in cold climates. There are two main issues that should be further addressed: the first is the impact of freezing and thawing on the concrete in a broader range of applications, and the second is to establish with greater certainty the potential impact of deicing salts on the concrete, particularly because the open pore structure allows for faster infiltration of these salts into the concrete matrix than in traditional concrete pavement. The first known direct observation of pervious concrete's behavior on freezing was a laboratory experiment by the U.S. Army's Cold Regions Research and Engineering Laboratory (Korhonen and Bayer 1989). Samples of pervious concrete without air entrainment, reinforcement, or other treatment for frost damage protection were repeatedly frozen and thawed. At intervals during the testing sequence, samples were removed from the freezing cycle and put under compressive force to test their loss of breaking strength. Those that had been frozen in dry or damp (wetted, then drained) conditions showed little loss of strength over 160 freezing-and-thawing cycles. A later laboratory test (Yang and Jiang 2003) showed that after 25 cycles of freezing and thawing in air, the unconfined compressive strength of five samples decreased 15 to 23%. Similar samples that had been frozen in water-filled containers, however, progressively deteriorated. Assuring rapid drainage of a pervious slab into a well-drained base reservoir, however, is a critical preventative measure against the effects of freezing. In cold regions, air-entraining agents are routinely added to concrete to protect it from frost damage (AASHTO 1993). Experience primarily from building construction suggests that air entrainment improves the resistance of pervious concrete to damage from freezing-and-thawing cycles as it does for dense concrete (FCPA 1990; Monahan 1981; Neithalath et al. 2003). Liquid polymer and latex additives may help by sealing the cement binder's micropores and preventing the entry of water. Supplementary cementitious materials, various fibers, and liquid polymers can enhance concrete's strength, limit shrinkage, and thereby improve its resistance to freezing-and-thawing conditions and deicing chemicals (Pindado et al. 1999).

Field performance was investigated for approximately two dozen pervious concrete sites located in the states of Ohio, Kentucky, Indiana, Colorado, and Pennsylvania. In addition to field observations and nondestructive testing, laboratory testing was performed on cores removed from some of the test sites. The installations evaluated had generally performed well in freezing-and-thawing environments, with little maintenance required. They were, however, relatively new, so there is a need to follow up later on field performance (Delatte et al. 2007).

11.5—Porous grout

The technology of grout injection to provide structural support beneath foundations has been practiced in construction since 1802 (Houlsby 1990). The materials have traditionally been a mixture of portland cement, water, and often a filler, such as sand. This is mixed into slurry and pumped into the desired area, usually the interface between existing foundations and the in-place soil or rock, forming a structural bond that is rigid and not normally pervious. There are cases, however, in which hydraulic conductivity is desired so that the natural hydrostatic forces can be relieved without causing deterioration due to saturation, erosion, and piping. This has led to the widespread use of French drains (gravel), drainage blankets, and fabrics for drainage and prevention of erosion (geotextiles), where foundations are accessible during construction. This type of pumped-in-place pervious grout would fill a basic need in the construction industry, particularly in projects involving site remediation and retrofit. Example applications of this pumped, porous material include remediation of dams (Weaver 1991), tunnels, highways, canals, railroads, and environmental treatment. Porous grout materials that could be pumped were studied and reported by the Bechtel Corporation in 1995. The studies encompassed a wide range of pumped materials that had drainage properties. Several mixture proportions were developed and are in the testing phase (Yen et al. 2002).

11.6—Stormwater management

There are two important aspects to stormwater management: runoff control and water quality control. There have been several initial studies into the infiltration rates, hydraulic conductivity, and rational runoff coefficient for pervious concrete (Wanielista et al. 2007; Montes and Haselbach 2006; Wimberley et al. 2001; Valavala et al. 2006). Additional study is needed for infiltration through sloped pervious concrete surfaces and the variation of infiltration rates with aging and other environmental impacts. Water-quality issues for watersheds are increasingly important. Much of the material washing into streams, rivers, and eventually into groundwater comes from surface runoff contaminated with materials applied to the ground surface. The contaminants can be excess fertilizers and nutrients, pesticides, road salts, or other materials intentionally applied, from spills or debris such as gasoline and petroleum products from oil drips, and tire abrasion or other residue such as litter, animal waste, and fine dust. Some materials are quickly picked up or dissolved and carried by runoff while others, including insoluble greases and low-volatile content oils, may not.

Another source of runoff contaminant has been ineffective or unenforced control of runoff on bare earth, often from sites under development. Lack of effective erosion controls has resulted in significantly increased sediment loads in some areas. By controlling excess surface runoff using a properly designed pervious concrete pavement system, a reduction in peak stream velocity is possible. Erosion of streambeds is reduced, thereby reducing the sediment load carried by the stream. Washing large amounts of nutrients (compounds high in nitrogen and phosphorus) into the watershed has numerous consequences. Plant growth, particularly microbial biomass such as phytoplankton and algal blooms, is increased. Although plants produce oxygen while alive, when they die, they decay, using up available dissolved oxygen and increasing the biochemical oxygen demand (BOD). Creating or increasing BOD stress, can, under the most extreme conditions, lead to events such as fish kills. Plant growth in pervious concrete systems should be minimal due to the lack of sunlight. In many cases, but not in all, the initial stormwater runoff will carry a higher concentration of contaminants than later runoff. The initial rain will wash off the surface somewhat. The part of the runoff with a higher contaminant concentration is termed the first flush. In arid areas with long periods between rain, a seasonal first flush may also occur. One of the common goals of runoff control is to capture the first flush. This is particularly true when dealing with small catchment (drainage) areas.

The first flush may not occur in some of the following cases:

- Large catchment areas rarely show a first flush, as a steady stream of the first flush of areas farther and farther away from the outlet arrive over time;
- There may not be a first flush if pollutants are not easily washed away or dissolved; and
- Differences in pollutant load over time may be difficult to detect if the supply of pollutants is essentially continuous (for example, sediment from bare, easily eroded ground).

Relatively simple rules of thumb for selecting or approving designs and control features have often been used due to lack of sufficient local data combined with seasonal variations or effects and antecedent rainfall events. As a crude rule of thumb, the first flush occurs during the first 30 minutes to 1 hour for small sites, such as parking lots. When pervious concrete is used, the first hour of rain will generally be captured as a minimum. It is reasonable to assume that, at a minimum, the part of the runoff with the highest pollution load will also be captured. Pervious concrete pavements will carry the first flush into the pores of the concrete, and additional rain will carry the pollutants further into the system without returning them to the runoff stream. The natural cleaning effects of soil may then further clean the runoff. Adoption of specific types of mitigation devices and features depends on the site use, the types and quantities of pollutants anticipated, the estimated runoff, and site characteristics. While capturing the first flush of an area is often desirable, the disposal of the first flush and cleaning of the catch basin after removing the first flush can be technically challenging and expensive.

Research is needed to establish or confirm many of the observations and assumptions regarding pollution trapped by pervious concrete pavements (Rushton 2000). Several of the assumptions related to water quality that need to be confirmed are:

- Greases and low volatile content oils occurring routinely on parking areas, such as oil drips from vehicles, will probably be adsorbed onto the surface of the pervious concrete or into the pores of the pervious concrete, or will be degraded by the microbial community in the system (Pratt et al. 2002) and will not be transferred to groundwater or surface water in any significantly different quantities than with detention ponds. Recent studies have investigated the efficiency of pervious concretes in containing vehicular oil spills (Bhayani et al. 2007; Deo et al. 2008). Pervious concrete mixtures with porosities ranging from 13 to 25% were proportioned using two different-size aggregates. The oil retention and recovery was experimentally determined on 2 in. (50 mm) slices of pervious concrete specimens using a partition gravimetric method. An idealized pore-aperture model was used to develop a modeling framework for the oil retention in pervious concrete. The material parameters, as well as the input features that are most likely to influence the retention and recovery of oil, were identified. A genetic programming-based model was used to predict the oil retention in pervious concrete specimens. It was found that this modeling methodology provides good estimates of oil retention;

- Water carrying dissolved solids and nutrients into the soil from the pervious concrete will undergo natural filtering and purification such that the water reaching the groundwater table will be of roughly the same quality as runoff soaking in directly from the surface; and
- The maximum draw-down time for a pervious concrete system should be 3 to 5 days, which is consistent with detention pond design, and may occur with pervious concrete pavements constructed on clayey soils. As light is not available much past the surface, growth and subsequent decomposition of biomass due to high nutrient loads in the runoff will be minimal. As pervious concrete is not saturated for much of its service life, the pores are relatively small but not capillary in size, air is available to a large surface area compared with the volume, and there is little difference in the decomposition of biodegradable organic material compared with decomposition on the surface.

11.7—Environmental filtering/remediation potential

In addition to its potential for filtering or remediating stormwater-related pollutants (Tamai et al. 2004), there is interest in pervious concrete as a material for other environmental filtering or remediation purposes, especially in the agricultural and waste treatment industries. Pervious concrete has already been used for greenhouse floors. There is also interest in using pervious concrete as a paved surface for manure or sludge dewatering.

11.8—Surface deterioration and repair

As with any other pavement surface, especially those under heavy vehicle loads, there is expected to be aging and deterioration of the pervious concrete surface over time. Offenberg and Davy (2008) proposed a test method for determining the raveling potential of a pervious concrete mixture. This method uses a 4 in. (100 mm) tall, 4 in. (100 mm) diameter cylindrical specimen that has only been cured for 7 days. The specimen is tumbled in an apparatus typically used for ASTM C131. The raveling potential relates to the difference in specimen mass before and after testing. Further research is needed to quantify a mixture's potential for surface deterioration after field application and service, and to correlate this back to fresh properties.

Typical concrete surface treatments may not be applicable to pervious concrete, as many are surface sealants and may effectively impact the infiltration capability of the pervious pavement. Research is not only needed for surface treatments that can extend the life of a pervious concrete pavement and add to its sustainability and aesthetics, but for materials and methods for pavement repair as well.

11.9—Development and standardization of broader testing methods

The current established testing methods for concrete are in many cases not applicable to pervious concrete. Either new or modified testing methods need to be established that take into consideration the unique characteristics of pervious concrete. The most frequently cited variable that is tested on pervious concrete is porosity. There are, however, many different definitions for porosity (effective porosity, total porosity, drained porosity, void content) that are not well defined and are equally important, depending on the application and design need of the pervious system. A variety of porosity measurement techniques have been investigated on pervious concretes (Crouch et al. 2003; Neithalath 2004; Marolf et al. 2004; Neithalath et al. 2006; Montes et al. 2005). Standardization or referencing to these techniques is crucial for comparison of most characteristics and for design criteria of pervious concrete systems.

Field quality control and assurance tests need to be established. Methods for testing workability or consistency, like the slump test for plain concrete, are necessary quality control tools for the concrete producer, as are tests for compressive strength and air entrainment. Owner's quality assurance tests for strength and durability are significant needs for pervious concrete pavements.

There are also testing methods that need to be developed for pervious concrete that are not similar to any methods traditionally used in the concrete industry. For instance, field infiltration rate methods similar to those for other porous media are needed. In addition, pollutant removal testing methods would be beneficial to design and specify pervious concrete for its potential water quality benefits.

11.10—Nondestructive determination of performance and properties

One of the significant impediments to the widespread use of pervious concrete is the absence of test methods to evaluate or predict the performance of the material as placed and in service. Due to its open pore structure, conventional methods of concrete performance estimation are not applicable to pervious concrete. Of late, some novel test methods have been attempted for nondestructive pervious concrete property estimation. Because it is easy to saturate the pervious concrete specimen with an electrolyte of known electrical conductivity, the emphasis has been on using electrical property-based methods for performance estimation. The use of a modified parameter that can be derived from electrical conductivity has been used to predict the permeability of pervious concrete fairly accurately (Neithalath et al. 2006). Similar methods have also been extended to predict the acoustic absorption behavior of pervious concrete. Delatte et al. (2007) used ultrasonic pulse velocity (UPV) to investigate in-service pervious concrete pavements as well as extracted cores. Ultrasonic pulse velocity was found to correlate well with engineering properties such as strength and void ratio.

11.11—Urban heat island effect, carbonation, and other thermal properties

Conventional, dark pavement surfaces are considered to be large contributors to the urban heat island effect. There is a unique aspect of pervious concrete that may influence its impact on the urban heat island effect—its porous nature. Many porous media are considered to be insulators, and pervious concrete may have some of these characteristics. Pervious concrete, however, also consists of interconnected voids that may influence convection of heat into or out of the earth's surface. It is unknown which heat transfer processes dominate, and under what conditions. There is little or no research into the urban heat island impacts of using pervious concrete over other impervious pavement surfaces; therefore, additional information is greatly needed (Ferguson 2005). Similarly, the thermal aspects of pervious concrete may be important for determining remediation rates and other environmental process rates.

The use of pervious concrete may also have an impact on another aspect related to the global climate. There has been much research and concern about the levels of carbon dioxide in the atmosphere. Many researchers have performed life-cycle analyses of the contribution to the carbon dioxide in the atmosphere from many construction materials. Concrete has been shown to be a contributor in two ways: the first is in the energy use for making cement, if the energy source is a nonrenewable source; and the second is in the chemical process that forms cement from its source materials, which releases carbon dioxide as a by-product. Therefore, even if the carbon dioxide component from the energy use was eliminated, the manufacture of pervious concrete would still result in a net production of carbon dioxide. There is some current research, however, into the absorption of carbon dioxide back into concrete structures over time. This process, referred to as carbonation, involves a chemical change and can balance some of the carbon dioxide gain from the cement manufacturing process. Carbonation is usually slow under ambient conditions, but faster when traditional concrete has large surfaces exposed to the air. An example is when concrete is broken up and recycled for fill. Pervious concrete has a much larger surface area exposed than other concrete applications to the air, and may have a faster rate of carbonation. Research into this rate is needed so that the overall impact of using pervious concrete on the amounts of carbon dioxide in our atmosphere can be better understood.

11.12—Other novel applications and uses

There are many other novel applications for pervious concrete other than as pavement surfaces for stormwater control or as an environmental filter for dewatering processes. Its lower density may benefit its use in building construction to reduce structural needs.

Pervious concrete is sometimes referred to as EPC and has been shown to have some benefits in sound absorption. Some applications are as road surfaces and sound barriers (Neithalath et al. 2005b; Tamai et al. 2004). A number of European studies relating to sound absorption characteristics of pervious concrete are available and so are a few studies carried out in the U.S. (Neithalath 2004).

CHAPTER 12—THE ENVIRONMENT AND PERVIOUS CONCRETE

Pervious concrete is a unique and innovative means of managing stormwater (Fig. 12.1). From an environmental perspective, among its primary benefits is the reduction in the total volume of runoff that otherwise carries substantial amounts of pollutants into our local streams, rivers, lakes, and oceans. Costly infrastructure is committed to dealing with the sheer volume of stormwater and the ability to effectively remove significant amounts of pollutants is increasingly challenging. By infiltrating the stormwater, a recommended best management practice of the U.S. EPA for dealing with runoff, not only is the volume of stormwater greatly reduced but pervious concrete effectively provides "first flush pollution mitigation" where approximately 90% of the pollutants are carried away in the first inch (25 mm) of typical significant rain events. The filtration provided by the voided matrix within pervious concrete retains organic pollutants and naturally occurring microbial growth may provide further treatment before the pollutants that remain are eventually converted by native soils.

The infiltration provided by pervious concrete recharges groundwater, provides irrigation to nearby surface vegetation and tree root systems, and mitigates "thermal pollution," where traditional runoff significantly contributes to an increase in water temperatures negatively affecting the habitat of fish, aquatics, and vegetation within various bodies of water. The potential to harvest water for a variety of purposes is also enhanced. Pervious concrete may also absorb and retain less heat, and may require less night illumination than the most commonly used conventional pavement, giving it the potential to positively impact urban heat island mitigation and carbon footprint through energy reduction.

Fig. 12.1—Pervious concrete stormwater management system.

12.1—Pervious concrete and the LEED™ green building rating system

When pervious concrete is used in building site design, it can aid in the process of qualifying for numerous credits in the Leadership in Energy and Environmental Design (LEED™) green building rating system (Version 3.0 LEED™ 2009) as administered by the U.S. Green Building Council. With rapid changes in the LEED™ system and pervious concrete technology, the committee will post current information about this topic on the ACI Concrete Knowledge Center at http://www.concrete.org/tkc/knowledge_center.htm.

LEED™ 2009 provides a framework for evaluating building and site performance, and establishes sustainability goals by creating several minimum mandatory requirements and then awarding points in five main credit categories: sustainable sites (SS), water efficiency (WE), energy and atmosphere (EA), materials and resources (MR), and indoor environmental quality (IEQ). There are also two other credit categories: the innovation and design processes category (ID), which allows for innovation in design and exemplary performance; and the regional priorities category (RP), which allows for additional credit points based on important regional environmental or resource needs. LEED™ 2009 points are not necessarily gained directly by the use of a product, but rather by meeting a specific sustainability goal of the rating program.

Pervious concrete can contribute to many LEED™ 2009 categories, including: Sustainable Sites, Water Efficiency, Materials and Resources, and Innovation in Design (RMC 2006; Ashley 2008; USGBC 2005, 2009).

Some specific credits where pervious concrete can aid the designer in meeting sustainability goals include:

12.1.1 Stormwater Control: *LEED™ 2009 Credits SS-c6.1 Stormwater Design – Quantity Control and SS-c6.2 Stormwater Design – Qualtity Control*—The intent of these credits is to limit disruption and pollution of natural water flows by managing stormwater runoff, increasing on-site infiltration, and eliminating contaminants. Each are worth one point, and a project can earn an additional exemplary performance point by going beyond the credit requirements for both quantity and quality control. Pervious concrete can contribute to these credits by reducing stormwater flow, allowing water to soak through and infiltrate to the ground below. Pervious concrete can also reduce the pollutant loads by filtering contaminants as the water is transferred through the pavement.

On building sites where the existing imperviousness is greater than 50%, Credit SS-c6.1 requires reducing the rate and quantity of stormwater runoff by 25% from the 2-year, 24-hour design storm. On building sites where the existing imperviousness is less than 50%, one of the options specifies that the post-development peak discharge rate and quantity from the site should not exceed the predevelopment peak rate and quantity for both the 1-year and also the 2-year 24-hour design storms. In many cases, by incorporating a pervious concrete pavement system on site, the project can meet these criteria and thus obtain the LEED™ 2009 point for SS-c6.1. Note that percent imperviousness is not the same as percent impervious. Percent impervious represents the portions of a project site covered with essentially impervious surfaces such as roofs and traditional paving. However, percent imperviousness is based on all the site surfaces and their contribution to runoff. It is calculated in a manner similar to the rational runoff coefficient (Haselbach 2010).

SS-c6.2 requires that 80% of the average annual post-development total suspended solids (TSS) load is removed from 90% of the average annual rainfall. This amount of rain can be approximated in the LEED™ 2009 reference guide (USGBC 2009) as the first 1.0, 0.75 or 0.5 in. (25, 19 or 13 mm) of a rain event in humid, semiarid, and arid regions, respectively. The guide also indicates that infiltration of these volumes of rain onsite is an effective method for TSS removal. Therefore, pervious concrete would be an accepted method for attaining the point for SS-c6.2.

Guidance is not given concerning the amount by which requirements in both SS-c6.1 and SS-c6.2 must be exceeded to receive an additional exemplary performance point in LEED™ 2009. Extensive use of pervious concrete systems may have the potential for obtaining this additional point and it is recommended that designers inquire as to the availability of exemplary performance in stormwater management with the use of pervious concrete for their project on a case-by-case basis. In the future, more guidance might be found in the addenda to LEED™ 2009 or the credit interpretation replies (CIRs) available from the USGBC on the www.usgbc.org website.

12.1.2 Heat Island Effect: *LEED™ 2009 Credit SS-c7.1 Heat Island Effect – Non-Roof*—The intent of this credit is to reduce heat islands (thermal gradient differences between developed and undeveloped areas) to minimize impact on microclimate and human and wildlife habitat, and reduce urban energy demands. This credit requires any combination of the following for 50% of the site hardscape (sidewalks, parking lots, drives, and access roads): shading within 5 years of occupancy, paving materials with a solar reflectance index (SRI) of at least 29, and/or an open-grid paving system. The definition of open-grid paving system for the purposes of SS-c7.1 is one which is at least 50% open and is vegetated. (A second method to achieve this credit includes providing under cover parking areas for 50% of the parking spaces.)

As noted, LEED™ 2009 gives credit for minimizing the heat island effect by the addition of shading, which may be provided by trees planted in or around parking lots and other hardscapes. Pervious concrete pavement is ideal for protecting trees in a paved environment. (Many plants have difficulty growing in areas covered by impervious pavements, sidewalks, and landscaping because air and water have difficulty getting to the roots.) Pervious concrete pavements or sidewalks allow adjacent trees to receive more air and water and still permit full use of the pavement.

Pervious concrete may also act to reduce the heat island effect by absorbing less heat from solar radiation than darker pavements. However, permeable pavements do not reflect solar radiation in the same manner as traditional impervious

Fig. 12.2—Supplementary cementitious materials. From left to right: fly ash (Class C); metakaolin (calcined clay); silica fume; fly ash (Class F); slag; and calcined shale. (Reprinted with permission from Portland Cement Association.)

pavements, even those of similar color and material design; therefore, pervious concrete is not eligible for this credit in most cases based solely on the SRI. It is hoped that modified SRI criteria may be applied to pervious concrete in future revisions or addenda to LEED™ SS-c7.1. The reason for this is that the relatively open pore structure of pervious concrete may store and transmit less heat and, therefore, helping to lower heat island effects in urban areas (Kevern et al. 2009; Haselbach et al. 2011). Designers may wish to submit a credit interpretation request (CIR) to the USGBC for pervious concrete applications based on a combination of its porosity and SRI, to ask for a point(s) for reducing the urban heat island effect, based on new literature on the subject and also citing that the International Code Council (ICC) has modified the International Green Construction Code (IGCC) in Version 2 to allow for pervious concrete to be applied as a countermeasure to the urban heat island effect, regardless of its SRI (ICC 2010). This newest version of the IGCC states the following exception for the solar reflectance criteria of 29: "Pervious concrete pavements shall be allowed to be considered as a hardscape material that is deemed to comply with the criteria for solar reflectance and need not be tested in accordance with ASTM E1980.". Note that SS-c7.1 is worth one point in LEED™ 2009, but is also subject to an additional exemplary performance point if all the hardscape on the site is effectively shaded, open graded, or has a high solar reflectance.

As a generalization, a concrete producer can increase the solar reflectance of concrete through materials selection. As portland cements can vary in color, a lighter-colored cement could improve the solar reflectance of a pervious concrete mixture as well could the introduction of integral coloring (white), and the potential use of a supplementary cementitious material such as slag (usually noticeably lighter than conventional plain gray cement). The size, shape, gradation, and color of the aggregates could affect the amount of "open gradedness," which contributes to the lack of comparative albedo in pervious concrete. The technique and type of equipment a contractor uses for placing the concrete could also contribute to this. As test sections are highly recommended for most critical applications of pervious concrete, doing such early enough to allow for in-place specimens to be evaluated for solar reflectance index (SRI) prior to placement and be potentially prequalified, may be a practical means of acceptance.

12.1.3 Water Efficiency: *LEED™ 2009 Credit WE-c1 Water Efficient Landscaping*—The intent of this credit is to limit or eliminate the use of potable water or other natural surface or subsurface water resources available on or near the project site, for landscape irrigation. Two points are awarded in LEED™ 2009 if potable water for irrigation is reduced by 50% when compared to a mid-summer baseline case (Option 1). Pervious concrete systems can facilitate this in two ways. The granular sub-base (retention layer) under pervious concrete can be used to store stormwater for irrigation, helping to reduce the potable water demand. In addition, pervious concrete may aid in retaining water in the soils near landscape beds, reducing the need for irrigation. If no irrigation is required for a project, or if no potable water is used *and* the overall irrigation needs are less than half the baseline, then two additional points may be earned for a total of four points in WE-c1 (Option 2).

12.1.4 Materials and Resources: *LEED™ 2009 Credit MR-c4 Recycled Content*—The intent of this credit is to increase the demand for building products that have incorporated recycled content material reducing the impacts resulting from the extraction of new material. The requirements for these credits are the use of materials with recycled content such that the sum of post-consumer recycled content plus one-half of the pre-consumer recycled content constitutes at least 10%, 20%, or 30% (based on the dollar value of the material), for one point, two points, or a third exemplary performance point, respectively, of the total value of materials in the project. Most ready mixed concrete contains recycled materials in the form of supplementary cementitious materials (SCMs) such as fly ash, slag, or silica fume (Fig. 12.2). The use of SCMs or recycled aggregate in pervious concrete or base material contributes to recycled content needed for this credit. Supplementary cementitious materials are considered pre-consumer recycled material and recycled aggregate from a demolished project are considered post-consumer recycled material. This credit has special calculations specifically for cement and SCMs. In most cases, for a composite material, LEED™ 2009 specifies that one calculate the dollar value of the recycled content as a fraction of the mass of the material that is recycled, times the total value of the material. However, because cement is one of the most expensive ingredients in concrete by mass, this calculation can be modified so that the dollar value of the SCM recycled content is a fraction of the mass of the cementitious material only, times the value of cement.

12.1.5 Regional Materials: *LEED™ 2009 Credit MR-c5 Regional Materials*—The intent of this credit is to increase demand for building products that are extracted and manufactured locally, thereby reducing the environmental impacts resulting from their transportation and supporting the local economy. To meet the intent of this requirement, 10% (based

Fig. 12.3—Pervious concrete parking lot.

Fig. 12.4—Pervious concrete parking area.

on cost) of the total materials should be harvested, extracted, or recovered within 500 miles (805 km) of the project site. An additional point is awarded for 20% regional materials. The majority of materials in pervious concrete and most ready mixed concrete are considered regional materials. Projects with large amounts of concrete may meet the required 10% or 20% regional materials to meet this credit (Fig. 12.3 and Fig. 12.4). LEED™ 2009 also allows a third exemplary performance point for MR-c5. It is listed in the reference guide as being awarded for 30% regional materials (USGBC 2009); however, earlier versions of LEED™ awarded it for a minimum of 40% regional materials. It is recommended that project designers check the LEED™ 2009 addenda provided on the USGBC website (www.usgbc.org) to determine if the requirements have been modified for exemplary performance.

12.1.6 Innovation in Design: *LEED™ 2009 IDc1 Innovation in Design*—As previously discussed, several of the LEED™ 2009 credits allow for an additional point for exemplary performance (EP). This point is counted in the innovation in design (ID) category as an IDc1 point. LEED™ 2009 allows for a maximum of three EP points to be counted toward a project as an IDc1, and a maximum total of five IDc1 points. The other IDc1 points may come from innovation. Therefore, if other areas of exceptional environmental or energy performance related to pervious concrete systems can be shown, then these may have the potential for an IDc1 innovation point.

12.1.7 Regional Priorities: *LEED™ 2009 Regionally Priorities*—The USGBC chapters in the country were allowed to pick six credits in the five main LEED™ categories that they determined were priorities for their region. The regional priority (RP) credits are listed for each zip code in each state as they become available at www.usgbc.org/LEED2009. If a project earns one of the credits in this list of six for the zip code in which the project is sited, then an additional point is added to the point total for a maximum of four extra points in the RP category. The credits for which pervious concrete may play a role are sometimes listed. For instance, in the State of Washington, there are several locations that have designated WEc1 (Option2) as eligible for an additional RP point, and other locations have designated SSc6.1 for RP credit. Similarly, WEc1 (Option 2) and MRc5 (20% compliance) are frequently listed in Florida, and both SSc6.1 and SSc6.2 are often eligible for extra RP points in areas of Ohio.

CHAPTER 13—REFERENCES

13.1—Referenced standards and reports

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designations. The users of this document should check directly with the sponsoring group if it is desired to refer to the latest revision.

American Association of State Highway & Transportation Officials (AASHTO)

M-157	Standard Specification for Ready-Mixed Concrete
T-180	Standard Method of Test for Moisture-Density Relations of Soils Using a 4.54 kg (10-lb) Rammer and a 457-mm (18-in.) Drop

American Concrete Institute

301	Specifications for Structural Concrete
325.12R	Guide for Design of Jointed Concrete Pavements for Streets and Local Roads
330R	Guide for Design and Construction of Concrete Parking Lots
522.1	Specification for Pervious Concrete Pavement

ASTM International

C29/C29M	Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate
C33/C33M	Standard Specification for Concrete Aggregates
C39/C39M	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
C42/C42M	Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete

C94/C94M	Standard Specification for Ready-Mixed Concrete
C131	Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
C138/C138M	Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete
C140	Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units
C150/C150M	Standard Specification for Portland Cement
C171	Standard Specification for Sheet Materials for Curing Concrete
C260	Standard Specification for Air-Entraining Admixtures for Concrete
C494/C494M	Standard Specification for Chemical Admixtures for Concrete
C595/C595M	Standard Specification for Blended Hydraulic Cements
C618	Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete
C666/C666M	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C989	Standard Specification for Slag Cement for Use in Concrete and Mortars
C1157/C1157M	Standard Performance Specification for Hydraulic Cement
C1240	Standard Specification for Silica Fume Used in Cementitious Mixtures
C1399	Standard Test Method for Obtaining Average Residual-Strength of Fiber-Reinforced Concrete
C1688/C1688M	Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete
D422	Standard Test Method for Particle-Size Analysis of Soils
D448	Standard Classification for Sizes of Aggregate for Road and Bridge Construction
D698	Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3))
D1557	Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 (2,700 kN-m/m^3))
D1883	Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils
D2487	Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)
D3385	Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer
E1050	Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones, and a Digital Frequency Analysis System

These publications may be obtained from the following organizations:

American Association of State Highway & Transportation Officials (AASHTO)
444 North Capitol Street N.W., Suite 249
Washington, DC 20001
www.aashto.org

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
www.concrete.org

ASTM International
100 Barr Harbor Dr.
West Conshohocken, PA 19428
www.astm.org

13.2—Cited references

AASHTO, 1993, *Guide for Design of Pavement Structures*, Washington, DC, 640 pp.

Ahmad, S. H., and Shah, S. P., 1985, "Structural Properties of High Strength Concrete and its Implications for Precast Prestressed Concrete," *PCI Journal*, V. 30, No. 6, Nov./Dec., pp. 92-119.

Ashley, E., 2008, "Using Pervious Concrete to Achieve LEED™ Points," *Concrete in Focus*, National Ready Mixed Concrete Association, Skokie, IL, Winter, 4 pp.

Atlanta Regional Commission, 2001, *Georgia Stormwater Management Manual*, pp. 3.3-33 and 3.3-40.

Baas, W. P., 2006, "Pervious Concrete Pavement Surface Durability in a Freeze-Thaw Environment where Rain, Snow and Ice Storms are Common Occurrences," Ohio Ready-Mixed Concrete Association, 4 pp.

Backstrom, M., 2000, "Ground Temperature in Porous Pavement During Freezing and Thawing." *Journal of Transportation Engineering*, V. 126, No. 5, Sept./Oct, pp. 375-381.

Bell, F. G., 1993, *Engineering Treatment of Soils*, Taylor and Francis, 302 pp.

Bhayani, B.; Holsen, T. M.; and Neithalath, N., 2007, "Investigations on the Efficiency of Enhanced Porosity Concretes in Containing Vehicular Oil Spills," *Proceedings in CD of the International Conference on Sustainability of Construction Materials and Structures*, Coventry, UK, 8 pp.

Brite/Euram Report, 1994, "Surface Properties of Concrete Roads in Accordance with Traffic Safety and Reduction of Noise," *Brite/Euram Project BE3415*, 138 pp.

Crouch, L. K.; Cates, M. A.; Dotson, V. J.; Honeycutt, K. R.; and Badoe, D. A., 2003, "Measuring the Effective Air Void

Content of Portland Cement Pervious Pavements," *Cement, Concrete and Aggregates*, V. 25, No. 1, pp. 16-20.

Crouch, L. K.; Smith, N.; Walker, A. C.; Dunn, T. R.; and Sparkman, A., 2006, "Determining Pervious PCC Permeability with a Simple Triaxial Flexible-Wall Constant Head Permeameter," *TRB 85th Annual Meeting Compendium of Papers*, 18 pp.

Das, B., 1993, *Principles of Geotechnical Engineering*, PWS Publishing Co., Boston, MA, p. 146.

Debo, T. N., and Reese, A. J., 2002, *Municipal Storm Water Management*, second edition, CRC Press, 976 pp.

Delatte, N.; Miller, D.; and Mrkajic, A., 2007, "Field Performance Investigation on Parking Lot and Roadway Pavements: Final Report," *RMC Research & Education Foundation*, 79 pp.

Deo, O.; Bhayani, B.; Holsen, T. M.; and Neithalath, N., 2008, "Modeling the Retention of Oil in Enhanced Porosity Concretes," *Proceedings of the NRMCA Concrete Technology Forum*, Denver, CO.

Erickson, S., 2006, "Pervious Concrete Durability Testing," *Technical Report*, Viesko Quality Concrete, Salem, OR, 6 pp.

Florida Concrete and Products Association (FCPA), 1990, *Pervious Pavement Manual*, Orlando, FL, 57 pp.

Ferguson, B. K., 1994, *Stormwater Infiltration*, CRC Press, 288 pp.

Ferguson, B. K., 1998, *Introduction to Stormwater: Concept, Purpose, Design*, Wiley, 272 pp.

Ferguson, B. K., 2005, *Porous Pavements*, Taylor & Francis, New York, 600 pp.

Francis, A. M., 1965, "Early Concrete Buildings in Britain," *Concrete and Constructional Engineering*, London, V. 60, No. 2, Feb., pp. 73-75.

Ghafoori, N., 1995, "Development of No-Fines Concrete Pavement Applications," *Journal of Transportation Engineering*, V. 126, No. 3, May-June, pp. 283-288.

Haselbach, L., 2010, *The Engineering Guide to LEED—New Construction: Sustainable Construction for Engineers*, Second Edition, McGraw-Hill Professional, New York, 464 pp.

Haselbach, L.; Boyer, M.; Kevern, J.; and Schaefer, V., 2011, "Cyclic Heat Island Impacts in Traditional Versus Pervious Concrete Pavement Systems," *Transportation Research Record: Journal of the Transportation Research Board*, V. 2240, pp. 107-115.

Haselbach, L. M., and Freeman, R. M., 2006, "Vertical Porosity Distributions in Pervious Concrete Pavement," *ACI Materials Journal*, V. 103, No. 6, Nov.-Dec., pp. 452-458.

Haselbach, L. M.; Valavala, S.; and Montes, F., 2006, "Permeability Predictions for Sand Clogged Portland Cement Pervious Concrete Pavement Systems," *Journal of Environmental Management*, V. 81, No. 1, pp. 42-49.

Herod, S., 1981, "Porous Concrete Market Blooms in Greenhouse," *Modern Concrete*, Mar., pp. 40-44.

Houlsby, A. C., 1990, *Construction and Design of Cement Grouting*, John Wiley and Sons, 442 pp.

ICC, 2010, "International Green Construction Code," Public Version 2.0, International Code Council, Washington, DC, Nov., http://www.iccsafe.org/cs/igcc/pages/default.aspx

Jing, Y., and Guoliang, J., 2003, "Experimental Studies on Properties of Pervious Concrete Pavement Materials," *Cement and Concrete Research*, V. 33, No. 3, pp. 381-386.

Kevern, J.; Haselbach, L.; and Schaefer, V., 2009, "Hot Weather Comparative Heat Balances in Pervious Concrete and Impervious Concrete Pavement Systems," *Proceedings: The Second International Conference on Countermeasures to Urban Heat Islands*, Sept. 21-23, Berkeley, CA.

Kevern, J. T., and Schaefer, V. R., 2008, "Temperature Response in a Pervious Concrete System Designed for Stormwater Treatment," *Proceedings of the American Society of Civil Engineers GeoCongress*, New Orleans, LA, pp. 1137-1144.

Korhonen, C. J., and Bayer, J. J., 1989, "Porous Portland Cement Concrete as an Airport Runway Overlay," *Special Report 89-12*, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 20 pp.

Little, D. N.; Males, E. H.; Prusinski, J. R.; and Stewart, B., 2000, "Cementitious Stabilization, TRB Committee A2J01," 7 pp.

Low, K.; Harz, D.; and Neithalath, N., 2008, "Statistical Characterization of the Pore Structure of Enhanced Porosity Concretes," *Proceedings of the NRMCA Concrete Technology Forum*, Denver, CO.

Mahboub, K.; Canler, J.; Rathbone, R.; Robl, T.; and Davis, B., 2008, "The Effects of Compaction and Aggregate Gradation on Pervious Concrete," *Proceedings of the NRMCA Concrete Technology Forum*, Denver, CO.

Malhotra, V. M., 1969, "A Low-Cost Concrete Building," *Engineering News Record*, pp. 62-63.

Malhotra, V. M., 1976, "No-Fines Concrete—Its Properties and Applications," ACI JOURNAL, *Proceedings* V. 73, No. 11, Nov., pp. 628-644.

Marolf, A.; Neithalath, N.; Sell, E.; Wegner, K.; Weiss, J.; and Olek, J., 2004, "Influence of Aggregate Gradation on the Acoustic Absorption of Enhanced Porosity Concrete," *ACI Materials Journal*, V. 101, No. 1, Jan.-Feb., pp. 82-91.

Mata, L., and Leming, M., 2008, "Sedimentation Effects on Pervious Concrete," *Proceedings of the 2008 National Ready Mixed Concrete Association Concrete Technology Forum*, Denver, CO.

Mathis, D. E., 1990, "Permeable Bases—An Update," *PCA*, No. 8, Nov., pp. 3-4.

Maynard, D. P., 1970, "A No-Fines Road," *Concrete Construction*, V. 15, No. 3, pp. 116-117.

Medico, J. J., Jr., 1975, "Porous Pavement," U.S. Patent No. 3870422.

Meininger, R. C., 1988, "No-Fines Pervious Concrete for Paving," *Concrete International*, V. 10, Aug., pp. 20-27.

Monahan, A., 1981, "Porous Portland Cement Concrete; the State of Art," U.S. Army Engineer Waterways Experiment Station, Structures Laboratory, Vicksburg, MS., Jan., 27 pp.

Montes, F. and Haselbach, L. M., 2006, "Measuring Hydraulic Conductivity in Pervious Concrete," *Environmental Engineering Science*, Nov., 2006.

Montes, F.; Valavala, S.; and Haselbach, L. M., 2005, "A New Test Method for Porosity Measurements of Portland Cement Pervious Concrete," *Journal of ASTM International*, Jan., V. 2, No. 1.

Mulligan, A., 2005, "Attainable Compressive Strength of Pervious Concrete Paving Systems," master's thesis, University of Central Florida, 132 pp.

National Ready Mixed Concrete Association (NRMCA), 2004, "Freeze-Thaw Resistance of Pervious Concrete," Silver Spring, MD, 17 pp.

National Ready Mixed Concrete Association (NRMCA), 2007, Text Reference for Pervious Concrete Contractor Certification, *Publication 2PPCRT*, NRMCA, Silver Spring, MD, Feb., 60 pp.

Neithalath, N., 2004, "Development and Characterization of Acoustically Efficient Cementitious Materials," PhD thesis, Purdue University, West Lafayette, IN, 269 pp.

Neithalath, N.; Weiss, W. J.; and Olek, J., 2003, "Development of Quiet and Durable Porous Portland Cement Concrete Paving Materials," *Final Report*, The Institute for Safe, Quiet, and Durable Highways, 179 pp.

Neithalath, N.; Weiss, W. J.; and Olek, J., 2005a, "Modifying the Surface Texture to Reduce Noise in Portland Cement Concrete Pavements," *Report* No. SN 2878, Portland Cement Association, Skokie, IL, 67 pp.

Neithalath, N.; Weiss, J.; and Olek, J., 2005b, "Modeling the Effects of Pore Structure on the Acoustic Absorption of Enhanced Porosity Concrete," *Journal of Advanced Concrete Technology*, Japan Concrete Institute, V. 3, No. 1, Feb., pp. 29-40.

Neithalath, N.; Weiss, J.; and Olek, J., 2006, "Characterizing Enhanced Porosity Concrete Using Electrical Impedance to Predict its Acoustic and Hydraulic Performance," *Cement and Concrete Research*, V. 36, No. 11, pp. 2074-2085.

Nelson, P. M., and Phillips, S., 1994, "Designing Porous Road Surfaces to Reduce Traffic Noise," *Transportation Research Laboratory Annual Review*, TRL, Crow Thorne, England, 58 pp.

Nissoux, J. L.; Gnagne, C.; Marzin, J.; Lefebvre, J.-P.; and Pipien, G., 1993, "A Pervious Cement Concrete Wearing Course Below 73 dB(A)," *Proceedings of the Fifth International Conference on Concrete Pavement and Rehabilitation*, Purdue University, IN, V. 2, pp. 269-284.

Offenberg, M. 2005a, "Producing Pervious Pavements," *Concrete International*, V. 27, No. 3, Mar., pp. 50-54.

Offenberg, M., 2005b, "Pervious Concrete Pavement Permitting," *Land Development Today*, V. 1, No. 8, Aug., pp. 6-10.

Offenberg, M., and Davy, M., 2008, "Development of a Test Method for Assessing the Surface Durability of Pervious Concrete," *Proceedings of the National Ready-Mixed Concrete Association Concrete Technology Forum*, Denver, CO, 30 pp.

Onstenk, E.; Aguado, A.; Eickschen, E.; and Josa, A., 1993, "Laboratory Study of Porous Concrete for Its Use as Top Layer of Concrete Pavements," *Proceedings of the Fifth International Conference on Concrete Pavement and Rehabilitation*, Purdue University, IN, V. 2, pp. 125-139.

Paine, J. E., 1990, "Stormwater Design Guide, Portland Cement Pervious Pavement," Florida Concrete and Products Association, Orlando, FL, 13 pp.

Pindado, M. A.; Aguado, A.; and Josa, A., 1999, "Fatigue Behavior of Polymer-Modified Porous Concretes," *Cement and Concrete Research*, V. 29, No. 7, pp. 1077-1083.

Pratt, C.; Wilson, S.; and Cooper, P., 2002, "Source Control Using Constructed Pervious Surfaces. Hydraulic, Structural and Water Quality Performance Issues," CIRIA, 152 pp.

RMC Research Foundation, 2006, *Ready Mixed Concrete Industry LEED™ Reference Guide*, National Ready Mixed Concrete Association, Silver Spring, MD.

Rushton, B., 2000, "Low Impact Parking Lot Design Reduces Runoff and Pollutant Loads," Southwest Florida Water Management District, Brooksville, FL, 225 pp.

Schaefer, V. R.; Wang, K.; Suleiman, M. T.; and Kevern, J. T., 2006, "Mix Design Development for Pervious Concrete in Cold Weather Climates," National Concrete Pavement Technology Center, 85 pp.

SI Concrete Systems, 2002, "Fiber-Reinforced Pervious Concrete," *Project* 2120-36, Chattanooga, TN, Oct. 25.

Soil Conservation Service, 1986, "Urban Hydrology for Small Watersheds," *Technical Release* No. 55, Soil Conservation Service, U.S. Department of Agriculture, Washington, DC, 160 pp.

St. John's River Water Management District (SJRWMD), 1999, *Applicant's Handbooks: Regulation of Stormwater Management Systems*, Palatka, FL, 285 pp.

Suleiman, M.; Kevern, J.; Schaefer, V. R.; and Wang, K., 2006, "Effect of Compaction Energy on Pervious Concrete Properties," *Proceedings of the NRMCA Concrete Technology Forum: Focus on Pervious Concrete*, Nashville, TN, 8 pp.

Tamai, M.; Mitzuguchi, H.; Hatanaka, S.; Katahira, H.; Makazawa, T.; Yanagibashi, K.; and Kunieda, M., 2004, "Design, Construction, and Recent Applications of Porous Concrete in Japan," *Proceedings of the JCI Symposium on Design, Construction, and Recent Applications of Porous Concrete*, Japan Concrete Institute, Tokyo, 15 pp.

U.S. Bureau of Reclamation, 1947, "The Durability of Porous Concrete," Materials Laboratories Report No. 3-369, U.S. Department of the Interior, Washington, DC.

USGBC, 2005, *LEED-NC for New Construction, Reference Guide*, Version 2.2, first edition, U.S. Green Building Council, Washington, DC, Oct. 2005, with errata posted through Spring 2007 at www.usgbc.org.

USGBC, 2009, *LEED Reference Guide for Green Building Design and Construction*, 2009 Edition, U.S. Green Building Council, Washington, DC, Apr. 2009, with addenda posted through December 2, 2009 at www.usgbc.org.

Valavala, S.; Montes, F.; and Haselbach, L. M., 2006, "Area Rated Rational Coefficient Values for Portland Cement Pervious Concrete Pavement," *Journal of Hydrologic Engineering*, ASCE, V. 11, No. 3, pp. 257-260.

Wang, K.; Schaefer, V. R.; Kevern, J. T.; and Suleiman, M. T., 2006, "Development of Mix Proportion for Functional and Durable Pervious Concrete," *Proceedings of the*

NRMCA Concrete Technology Forum: Focus on Pervious Concrete, Nashville, TN, 12 pp.

Wang, K.; Kevern J.; and Schaefer, V., 2008, "Self Consolidating Pervious Concrete for Overlay Applications," *Proceedings of the National Ready-Mixed Concrete Association Concrete Technology Forum*, Denver, CO.

Wanielista, M.; Chopra, M.; Offenberg, M.; Spence, J.; and Ballock, C., 2005, "Performance of Pervious Concrete Pavements," Presentation: Stormwater Management for Highways, Transportation Research Board TRB AFB60, Washington, DC.

Wanielista, M.; Chopra, M.; Spence, J.; and Ballock, C., 2007, "Hydraulic Performance Assessment of Pervious Concrete Pavements for Stormwater Management Credit," Stormwater Management Academy, University of Central Florida, 81 pp.

Weaver, K., 1991, *Dam Foundation Grouting*, ASCE Press, pp. 29-30.

Wimberley, J. D.; Leming, M. L.; and Nunez, R. A., 2001, *Evaluation of Mechanical and Hydrological Properties of High-Voids Pervious Concrete*, North Carolina State University, Raleigh, NC, 39 pp.

Winer, R. R., 2000, *National Pollutant Removal Database for Stormwater Treatment Practices*, second edition, Center for Watershed Protection, Ellicott City, MD, 29 pp.

Wingerter, R., and Paine, J. E., 1989, *Field Performance Investigation*, Portland Cement Pervious Pavement, Concrete and Products Association, Orlando, FL, 16 pp.

Yang, J., and Jiang, G., 2003, "Experimental Study on Properties of Pervious Concrete Pavement Materials," *Cement and Concrete Research*, V. 33, pp. 381-386.

Yang, Z.; Brown, H.; and Cheney, A., 2006, "Influence of Moisture Conditions of Freeze and Thaw Durability of Portland Cement Pervious Concrete," *Proceedings of the NRMCA Concrete Technology Forum: Focus on Pervious Concrete*, 15 pp.

Yen, P. T.; Sundaram, P. N.; and Godwin, W. A., 2002, "Pumped-in-Place Permeable Grout Systems, Permeation Grouting," Bechtel Corporation Technical Grant, pp. 1-44.

Zouaghi, A.; Kumagai, M.; and Nakazawa, T., 2000, "Fundamental Study on Some Properties of Pervious Concrete and Its Applicability to Control Stormwater Run-off," *Transactions of the Japan Concrete Institute*, V. 22.

American Concrete Institute®
Advancing concrete knowledge

As ACI begins its second century of advancing concrete knowledge, its original chartered purpose remains “to provide a comradeship in finding the best ways to do concrete work of all kinds and in spreading knowledge.” In keeping with this purpose, ACI supports the following activities:

- Technical committees that produce consensus reports, guides, specifications, and codes.
- Spring and fall conventions to facilitate the work of its committees.
- Educational seminars that disseminate reliable information on concrete.
- Certification programs for personnel employed within the concrete industry.
- Student programs such as scholarships, internships, and competitions.
- Sponsoring and co-sponsoring international conferences and symposia.
- Formal coordination with several international concrete related societies.
- Periodicals: the *ACI Structural Journal* and the *ACI Materials Journal*, and *Concrete International*.

Benefits of membership include a subscription to *Concrete International* and to an ACI Journal. ACI members receive discounts of up to 40% on all ACI products and services, including documents, seminars and convention registration fees.

As a member of ACI, you join thousands of practitioners and professionals worldwide who share a commitment to maintain the highest industry standards for concrete technology, construction, and practices. In addition, ACI chapters provide opportunities for interaction of professionals and practitioners at a local level.

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
U.S.A.
Phone: 248-848-3700
Fax: 248-848-3701

www.concrete.org

Report on Pervious Concrete

The AMERICAN CONCRETE INSTITUTE

was founded in 1904 as a nonprofit membership organization dedicated to public service and representing the user interest in the field of concrete. ACI gathers and distributes information on the improvement of design, construction and maintenance of concrete products and structures. The work of ACI is conducted by individual ACI members and through volunteer committees composed of both members and non-members.

The committees, as well as ACI as a whole, operate under a consensus format, which assures all participants the right to have their views considered. Committee activities include the development of building codes and specifications; analysis of research and development results; presentation of construction and repair techniques; and education.

Individuals interested in the activities of ACI are encouraged to become a member. There are no educational or employment requirements. ACI's membership is composed of engineers, architects, scientists, contractors, educators, and representatives from a variety of companies and organizations.

Members are encouraged to participate in committee activities that relate to their specific areas of interest. For more information, contact ACI.

www.concrete.org

American Concrete Institute®
Advancing concrete knowledge