UNIVERSIDADE FEDERAL DE MINAS GERAIS

ESCOLA DE ENGENHARIA

CURSO DE PÓS-GRADUAÇÃO EM

ENGENHARIA METALÚRGICA E DE MINAS

Tese de Doutorado

“Influência de parâmetros microestruturais na durabilidade do concreto leve produzido com argila expandida”

Autor: Weber Guadagnin Moravia

Orientador: Prof. Wander Luiz Vasconcelos

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INFLUÊNCIA DE PARÂMETROS MICROESTRUTURAIS NA DURABILIDADE DO CONCRETO LEVE PRODUZIDO COM ARGILA EXPANDIDA

Tese de Doutorado apresentada ao Curso de Pós-Graduação em Engenharia Metalúrgica e de Minas da Universidade Federal de Minas Gerais.

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e a minha esposa Juliana,
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RESUMO

A baixa relação resistência-peso do concreto, quando comparada com a relação resistência-peso do aço, representa uma desvantagem desse material quando aplicado na construção civil. Podemos melhorar esta relação reduzindo a massa específica do concreto ou aumentando sua resistência mecânica. Atualmente, o concreto leve tem sido usado, em grande escala, para fins estruturais e para reduzir o peso próprio das estruturas de concreto. Entretanto, um dos mais importantes requisitos para o concreto, é ser durável sob certas condições de exposição, pois nas últimas décadas, o número de estruturas de concreto com algum tipo de deterioração aumentou consideravelmente, devido à exposição dessas estruturas à atmosfera urbana. Poucas pesquisas nessa área estudaram a durabilidade do concreto leve. Este trabalho tem como objetivo avaliar a influência de parâmetros microestruturais na durabilidade do concreto leve com agregado de argila expandida. Existe um consenso na literatura com relação às zonas de transição, indicando-as como regiões frágeis nos concretos. Portanto, mais atenção tem sido dada para a influencia da zona de transição entre o agregado graúdo e a matriz de cimento em diversas propriedades do concreto. A durabilidade do concreto leve estrutural foi estudada comparando-a com a do concreto convencional, avaliando, principalmente, a resistência térmica, o desgaste superficial, a penetração de fluidos agressivos, e a retração. Foram feitos ensaios de resistência à compressão, condutividade térmica, calor específico, difusividade térmica, resistência à abrasão, retração, e permeabilidade para avaliar a durabilidade dos concretos. Ensaios de análise química, difração de raios X, microscopia eletrônica de varredura (MEV), porosimetria por intrusão de mercúrio, atividade pozolânica, e análises térmicas (TG), (DTG) e (DTA) foram realizados para estudar os parâmetros microestruturais. Os resultados obtidos permitiram avaliar as influências desses parâmetros na durabilidade do concreto leve e do concreto convencional. Foi observada uma zona de transição mais densa e com melhor intertravamento mecânico entre a argila expandida e a matriz de cimento no concreto leve, em relação à existente entre a brita calcária e a matriz de cimento no concreto convencional. O concreto leve apresentou uma melhor performance em relação ao concreto convencional quando sua durabilidade foi avaliada por ensaios que estão diretamente relacionados à durabilidade dos concretos.

ABSTRACT

The low relation strength-weight of concrete, when compared to steel, constitutes a disadvantage of that material when applied in the construction. To improve this relation we can reduce the specific gravity of the concrete or increase its strength. Nowadays, lightweight concrete has been used in a larger scale for structural purposes and for reduction of the self weight of structures. However, one of the most important requirements of the concrete is that it should be durable under certain conditions of exposure, because in the last decades the number of concrete structures with some kind of deterioration has increased considerably, due to the exposure of those structures to an urban atmosphere. Few researches in this area study the durability of lightweight concrete. This work aims to evaluate the influence of the microstructural parameters of lightweight concrete using expanded clay as coarse aggregate in the durability of the material. There is a consensus in the literature indicating that the transition zone constitutes weak points in the structure of the concretes and more attention has been given to the influence of the transition zone between aggregate and the cement matrix in several properties of the concrete. The durability of structural lightweight aggregate concrete (LWAC) was studied in comparison to normal-weight concrete (NWC) evaluating, mainly, thermal resistance, surface wearing, penetration of fluids and shrinkage. Assays of compressive strength, thermal conductivity, specific heat, thermal diffusivity, abrasion resistance and shrinkage were done to evaluate the durability of the concretes. Chemical analysis, X-ray diffraction, scanning electron microscopy with microprobe analyzer (SEM-EDS), mercury intrusion porosimetry, pozolanic activity, and thermal analysis (TG), (DTG) and (DTA) were analyzed to study the microstructural parameters. The gotten results, had allowed predicting the influences of these parameters in the durability of the lightweight concrete and normal-weight concrete. A transition zone denser and with better mechanics interconnections was observed between expanded clay and cement matrix in lightweight aggregate concrete (LWAC) than the existing between the limestone aggregate and cement matrix in normal-weight concrete (NWC). The lightweight concrete presented a better performance than normal-weight concrete when it durability was evaluated by assays which have a directly relation with the durability of the concretes.

ORGANIZAÇÃO DA TESE

A estrutura desta tese segue uma divisão por capítulos de 1 a 10. O capítulo 1 apresenta a relevância do trabalho, os objetivos a serem atingidos e a introdução ao tema na forma de uma revisão bibliográfica resumida. Os demais capítulos correspondem a manuscritos a serem submetidos para a publicação em periódicos.

O capítulo 2 caracteriza a argila expandida, visando sua aplicação como agregado para a produção de concreto leve. São apresentadas as principais propriedades relacionadas às características dos agregados, como massa unitária, absorção de água e composição granulométrica. Foram discutidos ainda alguns cuidados que devem ser previstos na utilização desse material como agregado graúdo em concretos.

O capítulo 3 avalia propriedades físicas e mecânicas do concreto leve, comparando-as com as do concreto convencional. Foi dada maior ênfase ao melhor fator de eficiência do concreto leve, o que justifica sua aplicação em substituição ao concreto convencional.

Os capítulos 4 e 5 tratam do comportamento térmico do concreto leve em relação ao concreto convencional. No capítulo 4 são avaliadas várias propriedades térmicas dos concretos, enquanto que no capítulo 5, o foco está voltado para o efeito que as variações térmicas provocam nos concretos.

O capítulo 6 avalia o desgaste superficial por abrasão no concreto leve e no concreto convencional, comparando os resultados obtidos. Este capítulo apresenta o estudo da zona de transição entre os agregados graúdos e a matriz de cimento. Esse estudo auxiliou na compreensão dos resultados de resistência à abrasão obtidos.

O capítulo 7 avalia a durabilidade dos concretos quando expostos à ação de fluidos agressivos, a partir da análise de diversos ensaios de absorção e percolação de água, que simulam a penetração de soluções salinas e soluções ácidas. Nesse capítulo também foi estudado a porosidade dos concretos, considerado um importante parâmetro microestrutural, para a avaliação da durabilidade.

O capítulo 8 estuda, de forma mais detalhada, a zona de transição, avaliando os fenômenos físicos e químicos que ocorrem nessa região e suas influências nas propriedades e na durabilidade do concreto leve e do concreto convencional.

O capítulo 9 avalia a retração autógena e a retração por secagem, fenômenos considerados importantes quando se deseja avaliar a durabilidade de concretos, e quando se procura relacionar estes fenômenos com a formação de microfissuras.

O capítulo 10 utiliza um programa para avaliar algumas características dos agregados, comparando os resultados com os obtidos por outros métodos, apresentando, dessa forma, uma nova aplicação para o programa. Nesse capítulo são apresentados ainda modelos da zona de transição entre o agregado graúdo e a matriz de cimento para os dois tipos de concreto, com base nos resultados obtidos ao longo desse trabalho. Esses modelos podem auxiliar na compreensão das diferenças de comportamento verificadas entre o concreto leve e o concreto convencional.

CAPÍTULO 1

Relevância, Objetivos e Introdução

1.1 RELEVÂNCIA

O concreto tornou-se o material de construção civil mais utilizado pelo homem, sobrepujando o aço, o tijolo cerâmico e a madeira. Segundo BRUNAUER e COPELAND, apud MEHTA e MONTEIRO (1994), o homem não consome nenhum outro material em tal quantidade, a não ser a água.

As razões da maior utilização do concreto em relação aos outros materiais são: sua excelente durabilidade, devido a sua resistência à ação da água sem deterioração séria; facilidade na obtenção de diversas formas e volumes, devido à sua consistência plástica; baixo custo e disponibilidade dos principais componentes; e menor consumo de energia para sua obtenção (MEHTA e MONTEIRO, 1994).

Como exemplo da importância do concreto em obras de grande porte, podemos citar a Barragem de Itaipu, localizada na fronteira do Brasil-Paraguai, com custo estimado em 18,5 bilhões de dólares, onde foram utilizados vinte tipos de concreto, totalizando 12,5 milhões de metros cúbicos.

A brita de calcário ou de gnaisse é amplamente utilizada no preparo de misturas para a produção do concreto. No estado de São Paulo, a brita representa 48% do total de minério produzido. A atividade mineradora pode contribuir para a poluição da água, ar e solo, promovendo ruídos, vibrações (devido ao uso de explosivos) e assoreamento de rios. A poeira ou pó de pedra resultante do processo de obtenção de brita, quando inalada, pode danificar de forma irreversível o aparelho respiratório humano (CIÊNCIA, TECNOLOGIA & MEIO AMBIENTE, 1999).

Os estados de São Paulo e Rio de Janeiro não produzem toda a brita que necessitam. Isso encarece e dificulta a produção de concreto. Dessa forma, o estudo de outros tipos de agregado graúdo, cria alternativas de substituição do agregado convencional.

A baixa relação resistência-peso do concreto, quando comparada ao aço, constitui um problema econômico na construção de edifícios altos, pontes com grandes vãos e estruturas flutuantes. Para melhorarmos essa relação podemos diminuir a massa específica do concreto ou aumentar sua resistência. Nas últimas décadas, tem-se conseguido, com sucesso, uma redução da massa específica do concreto através da utilização de agregados leves. A massa específica aparente desse tipo de concreto é de aproximadamente 1600 kg/m^3 e a resistência à compressão apresenta valores de 25 MPa a 40 MPa (MEHTA e MONTEIRO, 1994).

O concreto com agregado leve é o tipo de concreto leve mais utilizado, devido à variedade de tipos de agregados com baixa densidade, que permitem a produção de concretos com diferentes tipos de aplicação. O concreto com agregado leve quando comparado aos outros tipos de concreto leve (aerado e sem finos), pode atingir resistências à compressão maiores (concreto leve estrutural), podendo ser usado estruturalmente.

Em geral, os concretos leves são mais caros do que os convencionais. Isso pode ser explicado pelo maior consumo de cimento, já que a quantidade de água necessária à mistura é maior devido à alta absorção dos agregados leves. No entanto, em alguns tipos de aplicação podemos ter uma redução do peso próprio da estrutura de concreto, permitindo uma redução das dimensões dos elementos estruturais, o que resultaria em um ganho econômico.

NEVILLE (1982), ressalte que:

> "... para muitas aplicações, as vantagens do concreto leve sobrepujam as desvantagens e há uma tendência acentuada, no mundo todo, no sentido de se utilizar cada vez mais o concreto leve, especialmente em usos novos, como em concreto protendido, em edifícios de grande altura e também em cascas de cobertura."

Para HAQUE et al (2004), o concreto leve é considerado um material de construção muito versátil, o qual oferece ganhos técnicos, econômicos e ambientais. Este tipo de concreto é considerado como um material de suma importância para a Engenharia nos próximos anos.

O concreto é um material compósito, constituído de agregados graúdos envolvidos por uma matriz de cimento, areia e água. O comportamento mecânico e a durabilidade do concreto são influenciados pelos tipos de agregados, pela matriz de argamassa cimento e pela zona de transição entre esta matriz e os agregados (ZANG e GJϕRV, 1991).

Pouco se sabe sobre a zona de transição devido a dificuldades experimentais. Entretanto, recentemente, mais atenção tem sido dada para a influência da zona de transição entre agregado e a matriz de cimento em várias propriedades do concreto. No entanto, a maioria dos trabalhos de pesquisa nesta área tem investigado agregados convencionais.

A estrutura físico/química do concreto varia com o tempo, com a umidade e a temperatura, o que torna muito difícil o estudo de concretos sob a óptica da Ciência e Engenharia dos Materiais. Por outro lado, as técnicas disponíveis atualmente para a caracterização estrutural dos materiais têm permitido relacionar composição, estrutura e processamento do material com suas propriedades, contribuindo, assim, para uma interação entre a Engenharia Civil e a Ciência e Engenharia de Materiais, para o desenvolvimento de concretos mais econômicos e com melhor desempenho.

1.2 OBJETIVO

O presente trabalho tem como objetivo avaliar a influência de parâmetros microestruturais, como a porosidade e a zona de transição entre o agregado graúdo e a matriz de cimento, na durabilidade do concreto leve produzido com agregados de argila expandida.

1.2.1 Objetivos específicos:

- Caracterizar a argila expandida para sua aplicação como agregado leve na produção de concretos.

- Avaliar as propriedades térmicas do concreto com agregado leve, tais como a condutividade térmica, a difusividade térmica, o calor específico, e a expansão térmica, e compará-las com as propriedades do concreto convencional.

- Avaliar o desgaste por abrasão no concreto leve e compará-lo com o do concreto de referência.

- Determinar a porosidade e a facilidade de penetração de fluidos agressivos nos concretos, a partir de ensaios de porosimetria por intrusão de mercúrio, absorção de água e de permeabilidade.

- Comparar a retração autógena e a retração por secagem entre os dois tipos de concreto.

- Determinar o teor de hidróxido de cálcio no concreto leve e no concreto de referência e compará-los.

- Obter indícios de uma zona de transição mais densa e homogênea entre a matriz de cimento e a argila expandida em relação à formada entre a argamassa de cimento e a brita calcária.

- Correlacionar os resultados obtidos nas análises e avaliações acima, com a durabilidade do concreto leve.

1.3 INTRODUÇÃO

1.3.1 Concreto

O concreto é um material de larga aplicação na Construção Civil, obtido pela composição de cimento Portland, agregados e água, podendo conter aditivos que também influenciam no seu desempenho. A proporção entre os seus constituintes (traço) deve atender às condições requeridas de resistência, trabalhabilidade e durabilidade.

1.3.2 Principais componentes do concreto

1.3.2.1 Cimento Portland

O cimento Portland é um pó fino acinzentado, constituído essencialmente de silicatos e aluminatos de cálcio, que, quando misturado com água, adquire propriedades tais como ser moldável e ser capaz de desenvolver elevada resistência mecânica ao longo do tempo.

O cimento Portland é o aglomerante mais importante e mais utilizado na Construção Civil. A denominação do cimento Portland é decorrente da semelhança do cimento fabricado industrialmente com a pedra de Portland, calcário extraído em Dorset, na Inglaterra.

Aglomerantes são materiais pulverulentos que se hidratam na presença de água formando uma pasta resistente capaz de aglutinar agregados, dando origem às argamassas e aos concretos.

1.3.2.2 Constituintes do cimento Portland

Os constituintes do cimento Portland se dividem entre aqueles que são fundamentais à sua composição e aqueles que estão presentes em menores proporções.

De acordo com MEHTA e MONTEIRO (1994) os principais componentes são:

CaO → Óxido de Cálcio (cal);
SiO_2 → Dióxido de Silício (sílica);
Fe_2O_3 → Óxido de Ferro (hematita);
Al_2O_3 → Óxido de Alumínio (alumina);
MgO → Óxido de Magnésio (magnésia);
SO_3 → Anidrido Sulfúrico.

Os componentes secundários, ou seja, aqueles presentes no cimento em menores proporções, são:

Na_2O → Óxido de Sódio;
K_2O → Óxido de Potássio;
TiO_2 → Óxido de Titânio;
Impurezas e outras substâncias de menor importância.

O cimento Portland, cujos constituintes foram citados anteriormente, é obtido a partir da mistura de matérias-primas como calcário e argila, em proporções adequadas, devidamente moídas e homogeneizadas. Quando submetido a temperaturas acima de 800°C, o $CaCO_3$ (carbonato de cálcio) que constitui o calcário se decompõe e passa para a forma de CaO (cal) e CO_2 (NEVILLE, 1982) segundo a Equação 3.1.

$$CaCO_3 \xrightarrow{\Delta} CaO + CO_2 \uparrow \qquad \text{(Equação 1.1)}$$

O CaO reage com Al_2O_3 (alumina), Fe_2O_3 (hematita) e SiO_2 (sílica), provenientes da argila, no interior do forno rotativo a temperaturas em torno de 1450°C, formando o clínquer e resultando nos seguintes compostos químicos (MEHTA e MONTEIRO, 1994):

$3\ CaO.SiO_2 = C_3S$ → Silicato tricálcico
$2\ CaO.SiO_2 = C_2S$ → Silicato dicálcico
$3\ CaO.Al_2O_3 = C_3A$ → Aluminato tricálcico
$4\ CaO.\ Al_2O_3.Fe_2O_3 = C_4AF$ → Ferro aluminato tetracálcico

O clínquer, depois de resfriado e moído, recebe a adição de gesso ($CaSO_4$ – sulfato de cálcio), com a finalidade de impedir que as reações de hidratação entre o cimento e a água, quando da utilização do cimento, sejam instantâneas.

1.3.2.3 Tipos de cimento Portland

Existem vários tipos de cimento Portland sendo produzidos, diferenciando-se pela sua composição química e por algumas adições durante o seu processamento, tais como, escória de alto forno, pozolanas, materiais carbonáceos, entre outros, resultando características e propriedades que devem ser consideradas na escolha do cimento para cada tipo de aplicação. Atualmente, no mercado nacional, podemos considerar as seguintes opções:

Cimento Portland Comum (CP I);
Cimento Portland Composto (CP II);
Cimento Portland de Alto-Forno (CP III);
Cimento Portland Pozolânico (CP IV);
Cimento Portland de Alta Resistência Inicial (CP V);
Cimento Portland Resistente a Sulfatos (RS);
Cimento Portland de Baixo Calor de Hidratação (BC);
Cimento Portland Branco (CPB);
Cimento Portland Petrolífero (CPP).

O Cimento Portland Comum (CP I) pode conter adição (CP I-S), neste caso de 1% a 5%, em massa, de material pozolânico, escória ou fíller (calcário finamente moído) e o restante de clínquer mais gesso. O Cimento Portland Composto (CP II-E, CP II-Z, CP II-F) tem adições de escória, pozolanas e fíller, respectivamente, em proporções maiores que no CP I-S. Já o Cimento Portland de Alto Forno (CP III) e o Cimento Portland Pozolânico (CP IV) contam com proporções maiores de adições: escórias, de 30% a 70% (CP III), e pozolanas de 15% a 50% (CP IV) (ASSOCIAÇÃO BRASILEIRA DE CIMENTO PORTLAND, 2004).

1.3.2.4 Agregados

Entende-se por agregado o material granular, geralmente inerte, de dimensões e propriedades adequadas para o uso em concretos e argamassas. O termo inerte é utilizado por se tratar de um material que não reage quimicamente com a água. Entretanto, esta denominação, não representa uma forma correta de se referenciar o agregado, pois a palavra inerte significa não reativo, mas em alguns casos, ocorrem reações químicas na zona de transição entre o agregado e a argamassa de cimento, areia e água.

Conforme a dimensão das partículas, existe uma terminologia que classifica o agregado em graúdo e miúdo. A NORMA BRASILEIRA REGISTRADA - NBR 7211 – Agregados para concreto - define o agregado graúdo como pedregulho ou a brita proveniente de rochas estáveis, ou a mistura de ambos, cujos grãos passam por uma peneira de malha quadrada com abertura nominal de 152 mm e ficam retidos na peneira ABNT 4,8 (N^o 4). Já o agregado miúdo é definido como areia de origem natural ou resultante do britamento de rochas estáveis, ou a mistura de ambas, cujos grãos passam pela peneira 4,8 mm e ficam retidos na peneira ABNT 0,075 mm (peneira N^o 200).

Os agregados, em geral, são materiais com valores comerciais menores que o do cimento, portanto influenciam diretamente no custo do concreto. Além disso, proporcionam uma menor retração das pastas formadas por cimento e água, e aumentam a resistência ao desgaste superficial dos concretos.

Algumas características dos agregados determinam importantes propriedades do concreto tanto no estado fresco quanto no estado endurecido. As principais dentre elas são: composição granulométrica, forma e textura superficial dos agregados, substâncias deletérias presentes e massa unitária.

Composição granulométrica é a distribuição dos grãos por faixas granulométricas, expressa em termos das porcentagens retidas acumuladas nas séries de peneiras da ABNT. Dentro da mesma classe de agregados graúdos ou miúdos, a composição granulométrica tem influência direta na trabalhabilidade do concreto e no seu custo. Por exemplo, areias muito grossa produzem misturas de concreto ásperas e pouco trabalháveis, enquanto que areias muito fina aumentam o consumo de água, e portanto o consumo de cimento para uma dada relação (água/cimento), aumentando o custo do concreto. Agregados que não possuem excesso ou deficiência nas faixas granulométricas produzem concretos mais trabalháveis e econômicos (MEHTA e MONTEIRO, 1994).

A forma e a textura superficial das partículas influenciam principalmente as propriedades do concreto no estado fresco em relação ao estado endurecido. Quanto à forma dos grãos, os agregados podem ser classificados como arredondados, angulosos ou lamelares (termo utilizado no Brasil, para formas achatadas ou alongadas) (MEHTA e MONTEIRO, 1994). A textura superficial é classificada e definida dependendo de quanto a superfície do agregado é lisa ou áspera, e pode ser classificada principalmente como vítrea, lisa, áspera ou porosa (NEVILLE, 1982).

As substâncias deletérias podem ocasionalmente estar contidas nos agregados miúdos e graúdos. Essas substâncias podem se apresentar sob a forma de argila em torrões e materiais friáveis, materiais pulverulentos ou impurezas orgânicas e devem ter os seus teores limitados (de acordo com a norma NBR 7211), de maneira a não prejudicar a qualidade do concreto, como por exemplo, a trabalhabilidade, a durabilidade, a pega ou o endurecimento.

Os agregados podem ser classificados quanto à sua massa unitária (relação entre a massa e o volume ocupado pelos sólidos e os vazios), em normais, leves, ou pesados, o que influencia no tipo de aplicação, como pode ser visto na Tabela I.1.

Tabela I. 1 – Classificação dos agregados segundo a massa unitária.

Classificação	Massa unitária γ (kg/dm^3)	Exemplos	Principais aplicações
Leves	$\gamma < 1$	escória de alto forno, argila expandida, vermiculita.	lajes de pontes, peças pré-moldadas, concretos para isolamento térmico e acústico.
Normais	$1 \leq \gamma \leq 2$	areia, brita e pedregulho	obras em geral.
Pesados	$\gamma > 2$	barita,linolita, magnesita	concretos estruturais para blindagem contra radiações.

Fonte: MEHTA e MONTEIRO, (1994).

1.3.2.5 Agregado leve

A massa unitária dos agregados mais utilizados em concretos convencionais varia de 1400 kg/m^3 a 1700 kg/m^3. Agregados com massa unitária menor que 1120 kg/m^3 são considerados leves, e possuem como principal característica uma estrutura altamente porosa. Esses agregados podem ser naturais ou produzidos industrialmente (COUTINHO, 1988).

Os agregados leves naturais geralmente são de origem vulcânica, como por exemplo, pedra-pomes, cinzas vulcânicas e tufa (NEVILLE, 1982). Devido ao fato de serem somente encontrados em alguns lugares, os usos dos agregados leves naturais não é muito difundido.

Os agregados artificiais são obtidos por tratamento térmico de uma variedade de materiais e são classificados com base na matéria prima utilizada e no processo de fabricação. Dentre os agregados artificiais, temos os resultantes da aplicação de calor para a expansão de argilas, poliestireno, ardósias, folhelhos, perlitas e vermiculitas e os provenientes de um processo especial de resfriamento, pelo qual se obtém uma expansão, como a escória de alto-forno (subproduto da fabricação de ferro gusa). A Figura 1.1 mostra um espectro dos agregados leves e dos correspondentes concretos.

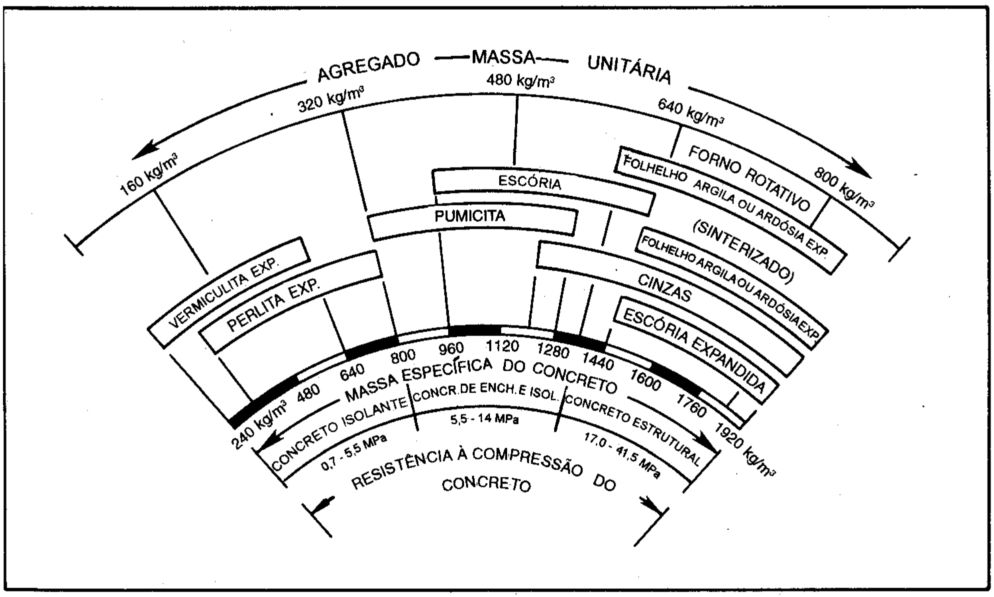


Figura 1. 1 – Espectro dos agregados leves e dos correspondentes concretos.
Fonte: MEHTA e MONTEIRO, (1994).

1.3.2.5.1 Argila expandida

Segundo COUTINHO (1988), a descoberta da argila expandida foi feita em 1885, mas só em 1918 o americano S. J. Heyde utilizou-a como agregado para concreto. O processo de fabricação do agregado de argila expandida, conhecido pela sigla LECA (light expanded clay aggregate), produzido em fornos rotativos foi patenteado na Dinamarca na década de 40. Na Figura 1.2 visualiza-se a argila expandida produzida em forno rotativo, utilizada como agregado graúdo em concreto leve.

Figura 1. 2 – LECA, agregado de argila expandida manufaturada em forno rotativo.
Fonte: SHORT e KINNIBURGH (1963).

A argila expandida é o produto obtido por aquecimento de alguns tipos de argila a temperatura entre 1000°C e 1200°C. Nesta faixa de temperatura, uma parte dos constituintes do material se funde gerando uma massa viscosa, enquanto que a outra parte se decompõe quimicamente, liberando gases que são incorporados por esta massa sinterizada, expandindo-a em até sete vezes o seu volume inicial. Esses gases, retidos no interior da argila, não podem escapar para o exterior devido à fase líquida que envolve as partículas da argila. Essa estrutura porosa se mantém após o resfriamento, de modo que a massa específica aparente do material resultante torna-se menor do que antes do aquecimento, podendo, o produto final, ser utilizado como agregado leve (SHORT e KINNIBURGH, 1963; KIYOHARA *et al*., 1982).

O agregado de argila expandida pode ser produzido pelo tratamento térmico da matéria prima triturada e classificada granulometricamente, ou moída e pelotizada, sendo este processo geralmente realizado em forno rotativo a gás ou óleo diesel, similar aos usados na fabricação de cimento Portland. Pode também ser obtido por sinterização contínua. Nesse caso, o material bem umedecido é transportado numa esteira, sob queimadores, de modo que o calor envolve gradualmente toda a espessura da camada (NEVILLE, 1982; MEHTA e MONTEIRO, 1994). A Figura 1.3 ilustra um forno rotativo utilizado para produção de argila expandida.

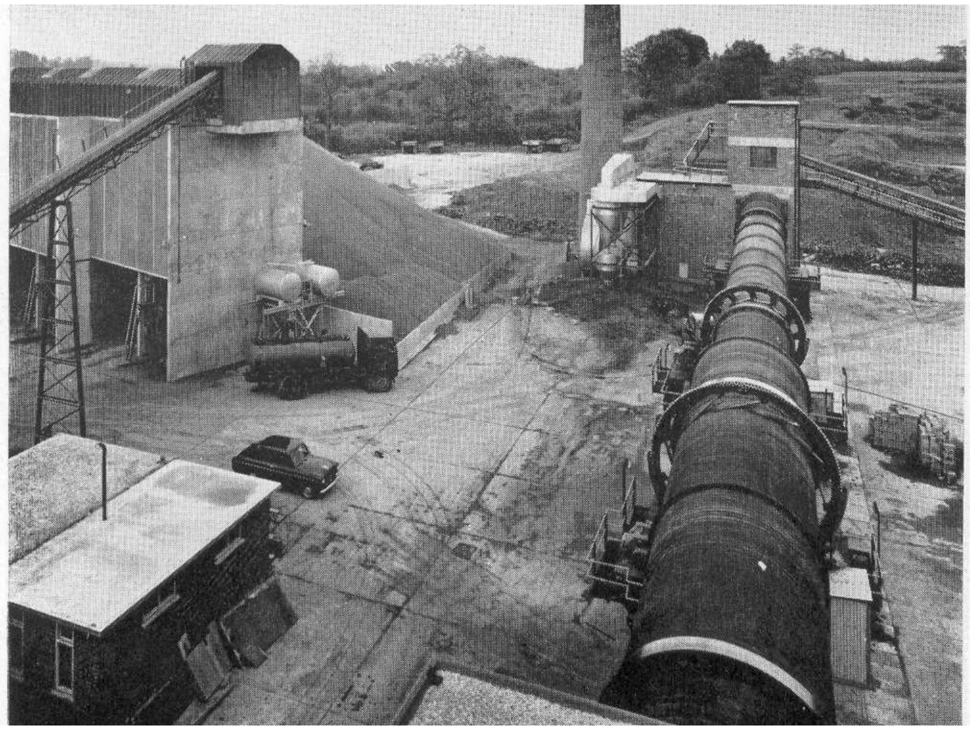


Figura 1. 3 – Forno rotativo usado para produção de argila expandida
Fonte: SHORT e KINNIBURGH (1963).

Os agregados de argila expandida produzidos pelo processo de sinterização contínua têm massa específica entre 650kg/m³ e 900kg/m³ e os produzidos em forno rotativo, entre 300kg/m³ e 650kg/m³ (NEVILLE, 1982).

SHORT e KINNIBURGH (1963) citam que para a produção destes agregados, a argila deve se fundir a temperaturas baixas e ao mesmo tempo, deve conter constituintes minerais que irão produzir gases em tal temperatura. Isso garante a produção desse agregado de forma econômica.

Os principais gases formados são: dióxido de enxofre, vapor de enxofre, dióxido de carbono, monóxido de carbono, oxigênio, hidrogênio e vapor de água. Estes gases resultam das reações entre os componentes minerais da argila e o carvão (COUTINHO, 1988).

Segundo MEHTA e MONTEIRO (1994), os álcalis e outras impurezas presentes na argila são os agentes responsáveis pela formação da massa viscosa a uma temperatura mais baixa (aproximadamente 600°C), enquanto os materiais carbonáceos são as fontes dos gases que proporcionam a expansão dessa massa.

A necessidade do aparecimento de uma fase em fusão (com viscosidade suficientemente elevada para aprisionar os gases) origina uma restrição na escolha da argila. Os teores de sílica, alumina e dos fundentes (cal, magnésia, óxido de ferro e álcalis) não devem ultrapassar determinados limites, sem os quais, a argila não se fundiria a temperatura mais baixas, ou se fundiria numa massa insuficientemente viscosa (COUTINHO,1988). Quando os constituintes minerais necessários para a fusão e para a produção dos gases não estão presentes na argila, eles podem ser incorporados durante a manufatura, misturando-se artificialmente pirita, hematita, dolomita, calcita, carvão ou combustíveis líquidos em pequenas porcentagens como óleo combustível, ou nafta (SHORT e KINNIBURGH, 1963; COUTINHO, 1988).

CALIXTO *et al*. (2001) ressaltam que a massa específica real da matéria-prima constituinte dos grãos expandidos é de aproximadamente 2,63 g/cm³. Quando moídos em grãos menores que 0,075mm, a argila expandida volta a apresentar as características da sua matéria-prima, pois a matriz porosa não mais existirá, já que a maioria dos seus poros possui tamanhos maiores que 0,075 mm de diâmetro, e a moagem irá destruí-los.

Para o concreto leve estrutural, recomenda-se o uso da argila expandida com dimensão máxima característica de 19mm. Grãos de argila expandida menores apresentam maior massa específica aparente e, conseqüentemente, maior resistência mecânica, devido ao menor volume de vazios. Além disso, para o caso de concretos mais fluídos, dimensões menores da argila expandida proporcionam menor segregação por flutuação do agregado graúdo (CALIXTO *et al.,* 2001).

A argila expandida possui uma alta absorção de água. Se mantida por mais do que 24 horas em contato com a água à pressão de 1 atm, é possível alcançar até 20% de absorção. Entretanto, se exposta a pressões acima de 1 atm (como acontece com o concreto bombeado, que chega de 100 atm a 120 atm), a absorção de água pode até dobrar, levando a uma descaracterização do traço por perda excessiva de plasticidade (slump), e um aumento da massa específica total do concreto devido à água que passa a ocupar os poros internos da argila (CALIXTO *et al.,* 2001).

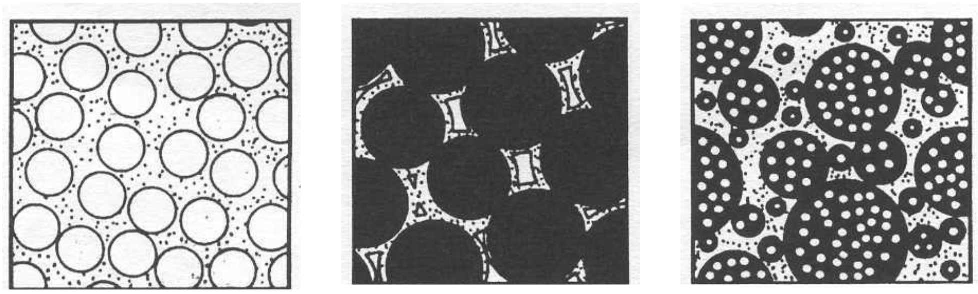
1.3.2.6 Água de amassamento

Água de amassamento é a água necessária para a hidratação dos compostos do cimento e para a trabalhabilidade do concreto. Essa água, quando potável, natural ou distribuída por uma Companhia de Abastecimento Municipal, tem qualidade suficiente para ser utilizada no amassamento do concreto.

O excesso de substâncias dissolvidas na água de amassamento do concreto pode afetar a resistência e o tempo de pega, devido aos íons que alteram as reações de hidratação, levando a reações de expansão e promovendo a corrosão da armadura. Maior quantidade de substâncias em suspensão pode impedir a cristalização dos produtos das reações de hidratação, interpondo-se entre os cristais em crescimento, diminuindo a coesão do concreto (COUTINHO, 1988).

1.3.3 Tipos de concreto leve

Os principais tipos de concreto leve são: concreto aerado, concreto sem finos e concreto com agregado leve. A Figura 1.4 ilustra, esquematicamente, os três tipos de concreto leve. Em essência, para todos os tipos, a redução da massa específica do concreto é obtida pela presença de vazios na sua estrutura. É claro que podem ser obtidos concretos leves com a combinação desses tipos, como por exemplo, o concreto sem finos combinado com agregados leves.



concreto aerado concreto sem finos concreto com agregado leve

Figura 1. 4 – Os três tipos de concreto leve.

Fonte: SHORT e KINNIBURGH (1963).

NEVILLE (1982), ressalta que:

"É evidente que a presença destes vazios reduz a resistência do concreto leve em relação ao concreto normal, mas em muitas aplicações a resistência não é fundamental. Os concretos leves proporcionam um bom isolamento térmico, e tem uma durabilidade satisfatória, mas não são muito resistentes à abrasão."

1.3.3.1 Concreto aerado

Consiste em um tipo de concreto onde são introduzidas bolhas na mistura ainda plástica de cimento e areia, de modo a produzir um material com estrutura celular. Por essa razão, o concreto é denominado concreto celular ou aerado. A rigor, o termo concreto não é apropriado, pois geralmente não é utilizado agregado graúdo.

Existem dois métodos, aplicados em concreto, para se produzir aeração:

No primeiro, a aeração é obtida através de uma reação que provoca o desprendimento de um gás no interior da argamassa fresca (cimento, água, areia), de modo que, após a pega, ela contenha uma grande quantidade de bolhas. A argamassa deve ter uma consistência adequada para que o gás consiga expandi-la sem escapar de seu interior. Assim, devem ser combinados a evolução do desprendimento de gás, a consistência da argamassa e o tempo de pega. Segundo NEVILLE (1982), normalmente é utilizado o alumínio em pó, finamente moído, em proporções da ordem de 0,2% da massa de cimento. A reação do pó de alumínio ativo com o hidróxido de cálcio libera hidrogênio, formando bolhas. Zinco em pó ou ligas de alumínio também podem ser usados. Às vezes, utiliza-se peróxido de hidrogênio, e neste caso é liberado o oxigênio.

No segundo método, a aeração é produzida pela adição de um agente espumante na argamassa. Em geral, utiliza-se uma forma de proteína hidrolisada, ou sabão de resina, que introduz e estabiliza bolhas de ar durante a mistura, a partir de uma rotação elevada. Em alguns processos, adiciona-se numa betoneira comum, durante a mistura, uma espuma estável, previamente formada (NEVILLE, 1982). Este tipo de concreto é utilizado na produção de blocos de concreto para a Construção Civil e são conhecidos como concretos altoclavados.

O concreto aerado apresenta retrações maiores do que nos concretos de agregados leves com igual resistência, devido à falta do agregado graúdo neste tipo de concreto. Além disso, as armaduras, quando não protegidas, são vulneráveis à corrosão, mesmo quando o ataque externo não é muito severo. Este fato é devido à alta porosidade desse tipo de concreto. Sendo assim, as armaduras devem ser protegidas por tratamento de imersão em líquidos anticorrosivos.

1.3.3.2 Concretos sem finos

Este tipo de concreto leve é obtido suprimindo-se o agregado miúdo, ou seja, o concreto sem finos é constituído somente de cimento, agregado graúdo e água.

O concreto sem finos é portanto, uma aglomeração de grãos de agregado graúdo, sendo cada um deles envolvido por uma camada de pasta de cimento (cimento mais água) de pequena espessura. Existem, por esse motivo, grandes poros no interior do concreto, que são os responsáveis pela baixa resistência mecânica e pela redução de massa específica.

O custo de concretos sem finos é relativamente baixo, pois o teor de cimento pode chegar a valores pequenos. Isso se deve à ausência das grandes áreas superficiais da areia que deveriam ser envolvidas pela pasta de cimento.

A massa específica desses concretos depende, principalmente, da granulometria do agregado graúdo. Podemos obter concretos com menor massa específica utilizando agregados com o mesmo tamanho de grão, pois agregados com uma granulometria bem distribuída vão preencher os vazios entre os grãos maiores, com grãos menores. Para agregados convencionais, a massa específica dos concretos sem finos varia entre 1600 e 2000 kg/m^3, mas usando-se agregados leves obtém-se massas específicas de até 640 kg/m^3 (NEVILLE, 1982).

Normalmente os concretos sem finos não são usados em concreto armado, mas quando necessário, a armadura deve ser revestida por uma camada fina, aproximadamente 3 mm, de pasta de cimento, para melhorar a aderência. Este tipo de concreto é mais utilizado em painéis para isolamento térmico e acústico.

1.3.3.3 Concreto com agregado leve

O concreto de agregado leve abrange um campo consideravelmente amplo, devido à variedade de tipos destes agregados, que permitem a produção de concretos leves com diferentes tipos de aplicação, o que torna este tipo de concreto leve mais utilizado.

Como principais aplicações, os concretos de agregados leve são utilizados em estruturas na forma de peças pré-moldadas, paredes moldadas *in loco*, lajes de edifícios com muitos pavimentos e tabuleiros de pontes com grandes vãos.

Quando comparado aos outros tipos de concreto leve, o concreto de agregado leve pode atingir resistências à compressão maiores (concreto leve estrutural), podendo ser usado estruturalmente. Além disso, apresenta menor retração em relação ao concreto aerado e melhor aderência nas barras de aço, quando comparado aos concretos sem finos.

Alguns agregados leves, mesmo com aparências semelhantes, podem resultar em concretos com propriedades muito diferentes, de modo que se faz necessária uma caracterização do agregado, a fim de conhecer suas propriedades antes da sua aplicação.

É difícil classificar os concretos de acordo com o tipo de agregado usado, pois as propriedades dos mesmos dependem também da granulometria dos agregados, do teor de cimento, da relação água/cimento e do grau de adensamento. No entanto, podemos ter uma noção da massa específica aparente do concreto com a utilização de alguns tipos de agregados leve, como mostra a Figura 1.5.

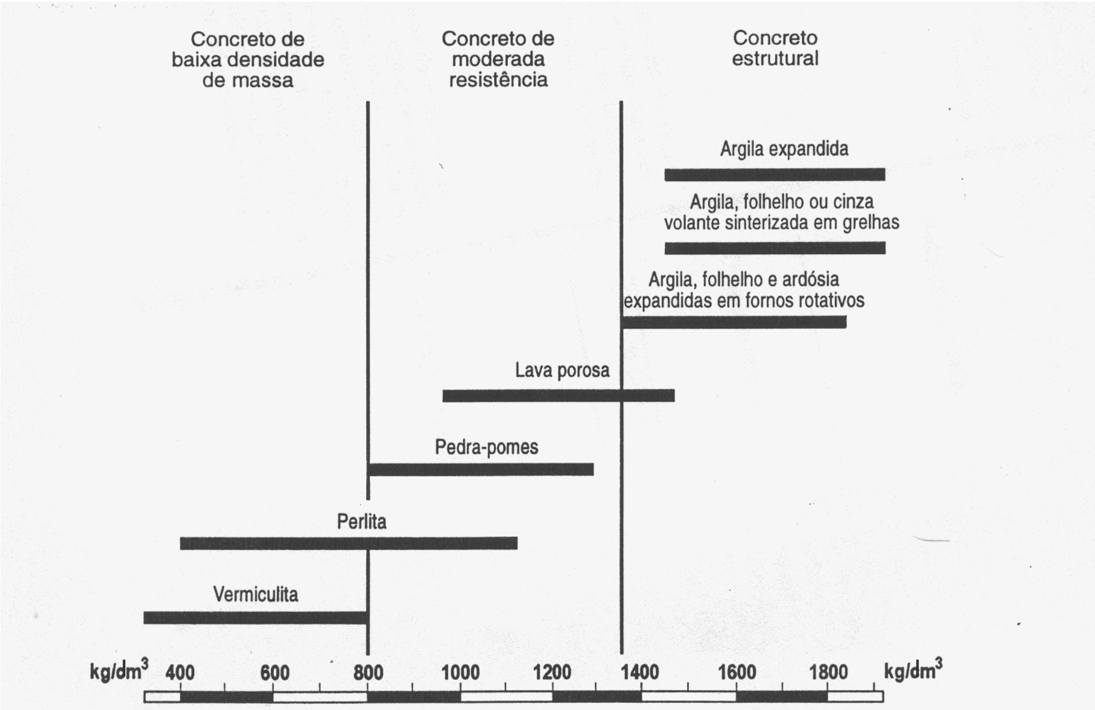


Figura 1. 5 - Relação do tipo de agregado leve com massa específica do concreto leve. Fonte: Sobral, (1996).

1.4 PROPRIEDADES DO CONCRETO LEVE ESTRUTURAL

Concreto leve estrutural é um concreto estrutural em todos os sentidos, exceto por utilizar agregados leves, com a finalidade de reduzir o peso próprio da estrutura e o custo total da obra. Portanto, para que o concreto seja classificado como concreto leve estrutural, as especificações de normas, como será visto nos itens 1.4.2 e 1.4.3, limitam a sua massa específica aparente e exigem uma resistência à compressão mínima, aos 28 dias, para assegurar a qualidade do concreto.

Dentre as principais propriedades do concreto podemos citar a trabalhabilidade, sua massa específica, a resistência à compressão, o módulo de elasticidade, a retração, sua absorção de água, a durabilidade e as propriedades térmicas.

1.4.1 Trabalhabilidade

Trabalhabilidade é a facilidade de manuseio do concreto durante a mistura, transporte, lançamento nas formas e adensamento sem segregação. Devido à baixa densidade e à textura porosa do agregado, a trabalhabilidade do concreto de agregado leve requer uma atenção especial.

Segundo MEHTA e MONTEIRO (1994), em concretos contendo agregado leve, o alto abatimento e a vibração excessiva podem proporcionar sedimentação da argamassa, mais pesada que o agregado leve, ficando em falta na superfície, onde é mais necessária para o acabamento de peças com grandes áreas como lajes e pavimentos. Esse fenômeno è denominado de segregação do agregado graúdo e é o inverso do que ocorre com o agregado convencional, onde a segregação resulta num excesso de argamassa na superfície.

A granulometria do agregado e o fator água/cimento exercem influência na trabalhabilidade dos concretos e devem ser considerados em conjunto, pois, quanto menor for a granulometria do agregado maior será a quantidade de água necessária para envolver os grãos do mesmo, formando uma película d'água responsável por uma boa trabalhabilidade. Portanto, a granulometria que produz uma boa trabalhabilidade para um dado fator água/cimento pode não ser a melhor para outro valor dessa relação.

Segundo a norma NBR 12821 – Preparação de concreto em laboratório - as argilas expandidas apresentam alto índice de absorção e, portanto, devem ser usadas somente após sua saturação.

KNIGHTS, apud LEITE (2001), estudando agregados reciclados de tijolos cerâmicos, sugere que apenas a absorção desse agregado relativa a 10 minutos de imersão em água, deve ser compensada no teor de água total colocado nas misturas de concreto, ao invés da taxa de absorção relativa a 24 horas de ensaio. Isto porque este foi considerado o tempo suficiente para reduzir a alta absorção dos agregados reciclados no estudo em questão.

LEITE (2001) concluiu em estudo realizado com várias amostras de agregado reciclados de tijolos cerâmicos que, após 5 minutos de imersão em água, as amostras atingiram 95% da absorção máxima. Deste modo, 5 minutos foi considerado tempo de saturação suficiente para efetuar uma pré-umidificação dos agregados.

1.4.2 Massa específica aparente

Define-se massa específica aparente como a relação entre a massa do material seco (em estufa a temperaturas entre 100°C e 110°C durante 24 horas) e o volume igual ao do sólido, geralmente expressa em quilograma por metro cúbico.

Segundo a norma americana AMERICAN SOCIETY FOR TESTING AND MATERIALS - ASTM C 330-77 (1991), a massa específica do concreto leve estrutural no estado seco não deve ser maior do que 1850 kg/m^3 e, deve apresentar valores entre 1400 e 1800 kg/m^3. O concreto leve isolante (sem função estrutural) geralmente tem massa específica menor que 800 kg/m^3.

A massa específica do concreto no estado endurecido é influenciada pela massa específica dos seus constituintes e pelas proporções da mistura. A granulometria e a forma dos grãos também podem influenciar, proporcionando uma melhor distribuição das partículas.

1.4.3 Resistência de dosagem

Segundo a ASTM C 330-77, o concreto leve estrutural deve ter uma resistência à compressão aos 28 dias de idade, determinada em corpo de prova cilíndrico padronizado, não inferior a 17 MPa.

De acordo com NEVILLE (1982), foram obtidas resistências à compressão de até 60 MPa, em concretos de agregado leve, com teores de cimento muito altos (560 kg/m^3). Um concreto de agregado leve com resistência à compressão de 20 MPa, por exemplo, pode consumir entre 240 kg e 400 kg de cimento por metro cúbico, dependendo do tipo de agregado. Para concretos com agregado leve e resistência à compressão igual a 30 MPa, o consumo de cimento fica entre 330 e 500 kg/m^3.

Geralmente, em concretos com agregado leve, o consumo de cimento pode superar em até dois terços os valores obtidos para concretos com agregado convencional, para uma mesma resistência.

1.4.4 Módulo de elasticidade

O módulo de elasticidade estático ou módulo de deformação elástica, para concretos, é obtido a partir da inclinação da curva tensão-deformação, sob carregamento uniaxial de tração ou compressão.

Segundo MEHTA e MONTEIRO (1994), temos três tipos de módulo de elasticidade estático:

O módulo tangente, que é dado pela inclinação de uma reta tangente à curva em qualquer ponto da mesma.

O módulo secante, que é dado pela inclinação de uma reta traçada da origem a um ponto da curva, correspondente a 40% da tensão de ruptura.

O módulo da corda, que é dado pela inclinação de uma reta traçada entre dois pontos da curva tensão-deformação. Um ponto representando uma deformação longitudinal de 50 μm/m ao ponto que corresponda a 40% da carga última.

SCHDELER apud NEVILLE (1982), encontrou para o módulo de elasticidade de concretos contendo argila expandida, com f_{ck} variando de 21MPa a 42MPa, valores entre 10,5 GPa e 14 GPa. Substituindo o agregado miúdo leve por areia natural, os módulos de elasticidade aumentam de 15% a 30%.

Segundo SWAMY e BANDYOPADHYAY, apud SOBRAL (1996), os dados obtidos para propriedades elásticas do concreto leve a partir de equações que correlacionem esta propriedade à resistência à compressão, ainda são muito falhos. Dessa forma, os autores sugerem a obtenção das propriedades elásticas do concreto leve experimentalmente.

1.4.5 Retração

As retrações em estruturas de concreto estão associadas às alterações dimensionais que ocorrem nas peças de concreto, sem que haja qualquer tipo de carregamento (AITÏCIN, 2000). Esse fenômeno é uma das principais causas da fissuração no concreto e sua ocorrência está associada à durabilidade deste material. Dentre os fatores que influenciam a retração podemos citar: o tipo litológico, as propriedades elásticas e a dimensão máxima característica dos agregados; o fator água/cimento, e a interface pasta/agregado (FURNAS, 1997).

NEVILLE (1982) sugere que a utilização de agregados leves em concretos resulta em retrações maiores do que as observadas em concretos convencionais. No entanto, AITÏCIN (2000), estudando a retração por secagem em concretos com agregados leves de folhelho expandido, encontrou retrações de 30% a 50% menores em relação às obtidas em concretos convencionais.

Essa diferença de opiniões pode ser explicada pelos vários tipos de agregados leves, com diversidade na matéria prima e no processo de fabricação, resultando em produtos com comportamentos distintos.

1.4.6 Absorção de água

A água pode transportar agentes agressivos ao concreto ou dissolver compostos desse material, proporcionando reações químicas de deterioração conforme será detalhado no item 1.5.2.

Os mecanismos relacionados ao transporte de fluidos ou de íons dissolvidos para o interior do concreto podem ocorrer por: permeabilidade, difusão, absorção capilar e migração. A permeabilidade é a medida do fluxo de um fluído devido a diferenças de pressão; a difusão é o processo que equilibra gradientes de concentração; a absorção capilar, por sua vez, se deve às forças capilares; enquanto que a migração é o fluxo de íons, quando existe uma diferença de potencial elétrico (NEPOMUCENO, 2005).

A durabilidade das estruturas de concreto pode ser avaliada indiretamente a partir de métodos que simulam os mecanismos de transportes de fluidos.

1.4.7 Propriedades térmicas do concreto

Na maioria dos materiais de construção existe uma relação direta entre a mudança de temperatura e as alterações dimensionais. Sendo assim, o estudo das propriedades térmicas do concreto é extremamente importante para que possamos conhecer, compreender e prever o comportamento deste material com a variação de temperatura. As propriedades térmicas dos concretos de cimento Portland são, muitas vezes, ignoradas e pouco entendidas pelos profissionais da Construção Civil.

As principais propriedades térmicas de interesse no concreto são: a condutividade térmica, a difusividade térmica, o calor específico e o coeficiente de dilatação térmica.

1.5 DURABILIDADE

A durabilidade do concreto é uma das principais razões da especificação desse material em diversas aplicações. Quando realizado um controle tecnológico, o concreto torna-se um material estável podendo resistir à deterioração por muitos anos. No entanto, quando submetido ao ataque físico ou químico, sua durabilidade pode ser reduzida (DEPUY, 1994).

As causas da deterioração dos concretos são decorrentes da ação de um ou mais agentes, que atuam de forma simultânea e progressiva por meio de mecanismos de degradação, reduzindo o desempenho e a vida útil dos concretos. A relação entre as principais origens e causas que levarão à queda de desempenho dos mesmos, por meio dos mecanismos de degradação estão apresentados na Tabela I.2.

Tabela I. 2 – Relações entre as origens, causas e sintomas da deterioração do concreto armado.

Origem da Deterioração	Causa			Sintoma
Mecânica	Sobrecarga			Fissuração
	Impacto			
	Cargas cíclicas			
	Restrição à variação de volumes sob gradientes normais de temperatura e umidade			
Física	Desgaste superficial	Atrito	Abrasão	Desgaste superficial
			Erosão	
		Cavitação		
	Cristalização de sais			Fissuração
				Escamamento
	Congelamento e degelo			Expansão Fissuração Escamamento
	Fogo			Fissuração Lascamento Desidratação da pasta
Química	Lixiviação			Dissolução Decomposição química
	Troca iônica	Ação dos sais		
		Ação dos ácidos		
	Formação de compostos expansivos	Sulfatos de sódio, potássio, cálcio e magnésio		Expansão Fissuração Decomposição química
		Reação álcali-agregado		Expansão Fissuração
		Hidratação MgO e CaO		
	Corrosão da armadura			Expansão Fissuração
	Biológica			Dissolução Decomposição química

Fonte: ANDRADE, (2005).

1.5.1 Causas físicas de deterioração

A deterioração física dos concretos está relacionada a esforços expansivos que normalmente provocam fissuras e desplacamentos, o que contribui, posteriormente, para a deterioração química.

Os principais tipos de deterioração física são apresentados nos itens abaixo:

1.5.1.1 Deterioração por desgaste superficial

A durabilidade do concreto pode ser seriamente comprometida sob a ação desse fenômeno em ciclos repetitivos, afetando principalmente a pasta de cimento endurecida, que possui baixa resistência ao atrito (MEHTA e MONTEIRO, 1994). Dessa forma o agregado graúdo, dentre outras finalidades, contribui para o aumento da resistência ao desgaste superficial.

De acordo com ANDRADE (2005), dentre os principais fatores que influenciam a resistência à abrasão do concreto, pode-se citar:

A dureza do agregado graúdo;
A aderência entre a argamassa e o agregado;
O controle da taxa de exsudação de água;
A cura adequada;
A menor porosidade;
A maior resistência à compressão do concreto.

Segundo ANDRADE (2005), existem poucos trabalhos brasileiros referentes ao estudo do desgaste superficial do concreto, e ensaios que tentam simular as formas de abrasão "podem ser bastante proveitosos para estudos comparativos entre diversos concretos, variando os fatores que podem influenciar no desgaste, permitindo o estudo de mecanismos e o desenvolvimento de concretos mais resistentes".

No Brasil, existe apenas um método de ensaio padronizado para avaliar a resistência à abrasão de materiais inorgânicos, descrito na norma NBR 12042 – Materiais inorgânicos – determinação do desgaste por abrasão. Além desse método, há outro ensaio padronizado pela norma NM 51 – Agregado Graúdo – Ensaio de Abrasão "Los Angeles", que avalia a resistência à abrasão dos agregados.

1.5.1.2 Deterioração por cristalização de sais nos poros

A cristalização de sais no interior dos poros capilares do concreto ocorre devido à evaporação da água e posterior rehidratação destes sais. A condição crítica está relacionada a ciclos de secagem e umedecimento, que favorecem a cristalização com aumento de volume, promovendo tensões internas e fissuração. Desta forma, segundo NEVILLE (1982), os concretos imersos permanentemente em soluções salinas são menos afetados por esse efeito.

Sais como o carbonato de sódio, sulfato de sódio e cloreto de cálcio, dentre outros, podem se cristalizar causando fissuração. As pressões internas vão depender da característica do sal, sua concentração e temperatura (MEHTA e MONTEIRO, 1994).

De acordo com ANDRADE (2005), "os concretos sujeitos à ação física da cristalização dos sais são aqueles com elevada relação água/cimento, isto é, porosos, que estejam em contato com soluções de alta concentração salina".

1.5.1.3 Deterioração por ação do congelamento

Esse tipo de deterioração não é muito observado no Brasil, país de clima tropical, onde poucas regiões apresentam temperaturas negativas durante o ano. No entanto, seus efeitos em estruturas de concreto são um dos maiores problemas em paises com climas muito frios, requerendo grandes gastos com manutenção e reparo dessas estruturas.

As causas mais comuns da deterioração por congelamento são: a fissuração, devido à expansão da argamassa causada pelo aumento em torno de 9% do volume da água, durante ciclos repetitivos de congelamento e descongelamento, e o descascamento da superfície do concreto, provocado por produtos químicos utilizados para o descongelamento (ANDRADE, 2005).

Segundo MEHTA e MONTEIRO (1994), "a incorporação de ar tem provado ser uma maneira efetiva de reduzir o risco de danos ao concreto pela ação do congelamento". Isso pode ser explicado pela produção de vazios na pasta de cimento, devido à incorporação de ar, que limitam o crescimento dos cristais de gelo, aliviando a pressão hidráulica no interior do concreto.

O tipo de agregado graúdo pode influenciar na resistência do concreto ao congelamento. As dimensões dos poros dos agregados geralmente são bem maiores que as da argamassa de cimento, contribuindo para uma maior permeabilidade e menores pressões hidráulicas, no interior do agregado, durante o congelamento. Dessa forma, os agregados podem suportar os esforços sem entrar em colapso (ANDRADE, 2005).

1.5.1.4 Deterioração pela ação do fogo

As estruturas de concreto possuem excelente resistência ao fogo, quando comparadas com estruturas metálicas ou com estruturas de outros materiais. A maioria dos autores atribui essa resistência à baixa condutividade térmica do concreto.

Os agregados possuem uma forte influência no comportamento mecânico do concreto a temperaturas elevadas. MEHTA e MONTEIRO (1994), afirmam que a porosidade e a mineralogia dos agregados são os principais fatores de influência. Agregados silicosos contendo quartzo, tais como granito e arenito, podem causar danos no concreto a temperaturas em torno de 573°C, porque nesta faixa de temperatura ocorre a transformação da forma α-quartzo para a β-quartzo, associada a uma expansão da ordem de 0,85 por cento. No caso de rochas carbonáticas, como o calcário, um dano similar pode começar acima de 700°C como resultado da decomposição do carbonato de cálcio.

1.5.2 Causas químicas da deterioração

O concreto está mais susceptível à deterioração química do que a outros tipos de deterioração. Como causas mais comuns de deterioração química podemos citar a ação dos sais e dos ácidos, e as reações expansivas como as que ocorrem na reação álcali-agregado. Segundo NEVILLE (1982), a resistência do concreto à deterioração química varia com o tipo de cimento, entretanto, a massa específica e a permeabilidade podem influenciar muito na durabilidade do concreto, chegando a prevalecer sobre o primeiro tipo.

1.5.2.1 Deterioração por ação dos sais

Os sais sólidos não atacam o concreto. No entanto, quando estes sais estão dissolvidos, ou seja, presentes em soluções, podem reagir com constituintes da pasta de cimento como o hidróxido de cálcio, formando produtos que originarão os mecanismos de deterioração.

O hidróxido de cálcio é mais solúvel em água e quimicamente reativo do que outros produtos de hidratação podendo reagir com sais dissolvidos, como cloretos e nitratos, pela troca de cátions entre o sal e a própria base, formando produtos que são retirados por lixiviação (DEPUY, 1994). A lixiviação implica no aumento da porosidade e na redução da resistência do concreto.

Alguns sais como os cloretos e nitratos, com cátions (Al, Fe, Mg), quando reagem com o hidróxido de cálcio, formam bases pouco solúveis porém de baixa alcalinidade. Isso contribui para a redução do pH do concreto e, conseqüentemente, para a corrosão das armaduras (ANDRADE, 2005).

1.5.2.2 Ataque de sulfatos

São sais encontrados principalmente nas águas do mar, águas subterrâneas, águas residuais de indústria e nas águas das chuvas.

Segundo NEVILLE (1982), a reação entre sulfatos e o $Ca(OH)_2$ e entre sulfatos e o aluminato tricálcico hidratado, formam o gesso ($CaSO_4.2H_2O$) e a etringita ($3CaO.Al_2O_3.3CaSO_4.31H_2O$), respectivamente. Esses produtos possuem um volume molecular consideravelmente maior que os compostos iniciais, podendo levar à expansão, fissuração e desagregação do concreto.

ANDRADE *et al* (1997) indica a permeabilidade como o fator determinante na difusão dos íons sulfatos para o interior do concreto. Segundo os autores “a difusão de íons sulfatos através dos poros do concreto é controlada por sua permeabilidade”.

NEVILLE (1982) cita que a vulnerabilidade dos concretos ao ataque de sulfatos pode ser reduzida adicionando ou substituindo parcialmente o cimento por pozolanas. Para o autor, esse material reage com o $Ca(OH)_2$ tornando inativas as fases que contém alumina. Outra maneira seria optar pelo uso de cimento com baixo teor de C_3A.

1.5.2.3 Deterioração por ação dos ácidos

Os concretos não apresentam boa resistência à ação dos ácidos, devido ao caráter básico da pasta de cimento, com pH em torno de 12,5. Entretanto, a taxa de ataque químico será função do pH do ácido e da permeabilidade do concreto. Se a permeabilidade do concreto for baixa e o pH das soluções ácidas for superior a 3, o concreto pode resistir à exposição ocasional desses ácidos (ANDRADE, 2005).

Soluções ácidas reagem com compostos da pasta de cimento, pela troca catiônica entre o ácido e o hidróxido de cálcio, formando sais de cálcio. Caso esses sais sejam solúveis, podem ser facilmente lixiviados, aumentando a porosidade e a permeabilidade da pasta e abrindo caminho para outros agentes de deterioração, fenômeno similar ao que ocorre com o ataque por sais (MEHTA e MONTEIRO 1994).

Além da redução da durabilidade, a lixiviação provoca a precipitação de crostas brancas de carbonato de cálcio ($CaCO_3$) na superfície do concreto, causadas pela evaporação da água e pela reação do produto lixiviado com o gás carbônico (CO_2) presente na atmosfera, resultando no fenômeno conhecido como eflorescência, que compromete o desempenho estético do concreto.

Segundo DEPUY (1994), o ataque de ácidos provoca a redução do pH do concreto, que contribui para a corrosão da armadura, decomposição química dos silicatos de cálcio hidratados e redução da resistência do concreto.

O ácido sulfúrico (H_2SO_4), formado nas atmosferas urbanas e industriais, por meio da reação entre os gases sulfurosos, provenientes da queima de combustíveis fósseis, com o vapor de água e o oxigênio, é um dos componentes da chuva ácida. Este ácido é agressivo ao concreto, pois ao reagir com o hidróxido de cálcio, produz o sulfato de cálcio, que induz a expansão e fissuração do concreto (ANDRADE, 2005).

1.5.2.4 Reação álcali-agregado

A reação álcali-agregado é um tipo de reação química de deterioração do concreto, que ocorre entre alguns constituintes da pasta de cimento e outros dos agregados. A reação química entre constituintes silicosos, provenientes do agregado, e hidróxidos alcalinos presente no cimento, como o hidróxido de sódio e o hidróxido de potássio, recebe o nome de reação álcali-agregado.

Segundo MEHTA e MONTEIRO (1994), os íons alcalinos podem ser fornecidos por outras fontes tais como: agregados contaminados com sais, aditivos contendo álcalis, presença água do mar ou soluções degelantes contendo cloreto de sódio.

Os produtos da reação álcali-agregado são expansivos e podem se manifestar por meio de: expansões, movimentações diferenciais, fissurações, exudação de gel e redução da resistência mecânica do concreto.

1.5.2.5 Carbonatação

Constituintes presentes na atmosfera podem produzir reações de neutralização do concreto. Segundo PAZINI (2005), esses principais constituintes são o gás carbônico (CO_2), o dióxido de enxofre (SO_2) e o gás sulfídrico (H_2S). Esse processo recebe o nome de carbonatação devido à maior ocorrência da reação, representada na Equação 1.2, em relação às outras reações de neutralização.

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O \qquad \text{(Equação 1.2)}$$

Segundo SMOLCZYK, apud PAZINI (2005), além do hidróxido de cálcio, outros compostos hidratados do cimento suscetíveis à carbonatação são o hidróxido de sódio (NaOH) e o hidróxido de potássio (KOH).

Essas reações consomem os íons hidroxílicos do concreto, reduzindo o seu caráter básico e o pH a valores inferiores a 9. Esta redução avança progressivamente para o interior do concreto, despassivando a armadura e contribuindo para a corrosão.

1.6 ZONA DE TRANSIÇÃO ENTRE AGREGADO E PASTA DE CIMENTO

Definimos zona de transição como a região entre materiais diferentes ou fases distintas, entre os quais existe uma área de contato denominada interface, onde estão presentes alguns tipos de ligações (MEHTA e MONTEIRO, 1985). Geralmente, a interface de maior interesse é aquela entre a matriz de cimento e o agregado graúdo que, no caso deste trabalho, é a argila expandida no concreto leve e a brita calcária no concreto convencional

Parece haver um consenso entre os diversos pesquisadores de que as regiões de interface constituem pontos fracos na estrutura do concreto e que, além disso, essas regiões influenciam claramente na resistência mecânica, aderência, módulo de ruptura, rigidez a flexão e permeabilidade desse material. Por outro lado, ainda não se sabe até que ponto as propriedades do concreto podem ser melhoradas por meio de incrementos na performance da ligação pasta agregado.

Segundo COUTINHO (1988), nos fenômeno de aderência que ocorrem na interface entre o agregado graúdo e argamassa de cimento, os principais tipos de ligações presentes são:

a) Ligação física – está relacionada às causas mecânicas como: forma e rugosidade do agregado, em nível macroestrutural; porosidade e absorção superficial do agregado, em nível microestrutural. Está ainda relacionada às forças eletrostáticas (forças de Van der Waals) entre a matriz de argamassa de cimento e a superfície do agregado.
b) Ligação epitáxica - Ligação regular entre cristais da matriz de argamassa de cimento e cristais do agregado graúdo, formando uma continuidade entre essas estruturas com ou sem formação de solução sólida.
c) Ligação química - Aderência devido às reações químicas entre os produtos de hidratação do cimento e a superfície do agregado graúdo.

É importante ressaltar que essas ligações não ocorrem isoladamente, pois um tipo de ligação pode ser conseqüência de outra forma de ligação, que se interagem, resultando na aderência entre agregado e matriz de cimento.

Ensaios em corpos de prova cilíndricos de concreto, submetidos à tração por compressão diametral, demonstram que em concretos com agregado leve a seção de ruptura passa através desse agregado, como pode ser visto na Figura 1.6a. Por outro lado, em concretos convencionais, o agregado graúdo é mais denso e resistente, e a fratura contorna esse agregado passando pela zona de transição e pela matriz de cimento, ilustrado na Figura 1.6b. (MEHTA e MONTEIRO 1994).

(a) Concreto leve (b) Concreto convencional

Figura 1. 6 – Planos de ruptura por compressão diametral nos concretos analisados.

Segundo METHA e MONTEIRO (1994), "com o aumento da idade, a resistência da zona de transição pode tornar-se igual ou mesmo maior do que a resistência da matriz" quando são utilizados agregados silicosos, que formam produtos como silicatos de cálcio hidratado durante a hidratação. No caso de agregados de calcário, as reações químicas de hidratação formam carboaluminatos hidratados, que cristalizam-se nos vazios da zona de transição contribuindo para sua resistência.

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CAPÍTULO 2 - Characterization of the Expanded Clay to Use as Lightweight Aggregate in Structural Concrete

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Authors: Weber Guadagnin Moravia, Carlos Augusto de Souza Oliveira,
Adriana Guerra Gumieri, Wander Luiz Vasconcelos.

Abstract

The use of expanded clay as aggregate is economically feasible in the manufacturing of concrete due to the decrease in specific gravity, provided by these aggregates, minimizing the self-weight of the structures. The objective of this work is to characterize the microstructure of expanded clay aggregates which are used in the manufacturing of lightweight concretes. The expanded clay was evaluated concerning of the density, the granulometry and water absorption after total immersion of the aggregate. The chemical analysis, scanning electron microscopy, X-ray diffraction and mercury intrusion porosimetry were used as well. The expanded clay presented a particle size distribution between the normal-weight aggregates grades 0 and 1 and high water absorption due to the high porosity of their grains. The X-ray diffraction data showed the presence of α-quartz, magnesium silicate and magnesium aluminum oxide.

Keywords: expanded clay, microstructure, lightweight concrete.

2.1 INTRODUCTION

The expanded clay is obtained by the heating some clay types in a temperature around 1200 °C. As the temperature approaches 1200ºC, a part of the components of the material merge producing a viscous paste, while the other part decomposes liberating gases that are chemically incorporated in this sintered paste, expanding it up to seven times its initial volume. The gases, kept inside the clay, cannot escape to its exterior due to the liquid phase that involves the clay particles. That porous structure remains after the cooling, so that the unitary mass of the resulting material becomes smaller than before the heating, and it may be used as coarse aggregate in the production of lightweight concrete, with the objective of reducing the self-weight of the structures [1-2-3].

The expanded clay aggregate can be produced by the thermal treatment of the raw material, triturated and composed granularly, or ground and in pellets, usually done in gas or diesel rotative oven, similar to the used in the production of Portland cement. It can also be obtained by continuous sintering. In that case, the moistened material is transported in a mat, under burners, so that the heat gradually reaches all the thickness of the layer [4-5]. The expanded clay aggregates, produced by the process of continuous sintering possess bulk density in an area between 650 kg/m³ and 900 kg/m³ and the produced in rotative oven, between 300 kg/m³ and 650 kg/m³ [5].

The aggregate's particle size distribution and the factor water/cement influence the workability of the concretes and they should be considered as a whole, because the smaller the aggregate's particle size a bigger amount of water will be needed to involve the grains, forming a water film responsible for a good workability [5].

The characterization of the expanded clay's microstructure is important for the production of the concretes, helping figure out the physiochemical reactions that happen in its interface with the cement matrix. Due to its high porosity, the expanded clay provides a reduction of the mechanical resistance of the concretes [6]. On the other hand, an important characteristic of the lightweight aggregate is the good adherence between the aggregate itself and the moisturized paste of cement that involves it. This adherence is due to the rough texture of the lightweight aggregate's surface, resulting in a mechanical interlocking between the aggregate and the paste

[7]. This adherence can also be improved due to the absorbed water by the aggregate in the moment of the mixing of the concrete, which with the giving time, becomes available for the hydration of the unhydrated cement [8-9]. Part of this hydration happens in the area of the aggregate-matrix interface, turning the adherence between the aggregate and the matrix more resistant [5].

The expanded clay studied was supplied by a company in the state of São Paulo and it is commercially available in the Brazilian market. Its raw material was obtained in the bay area of Bahia and processed in rotative oven. In order for the clay to have expansible characteristics, the chemical composition of the raw material should within of the areas presented in Fig 2.1 [2].

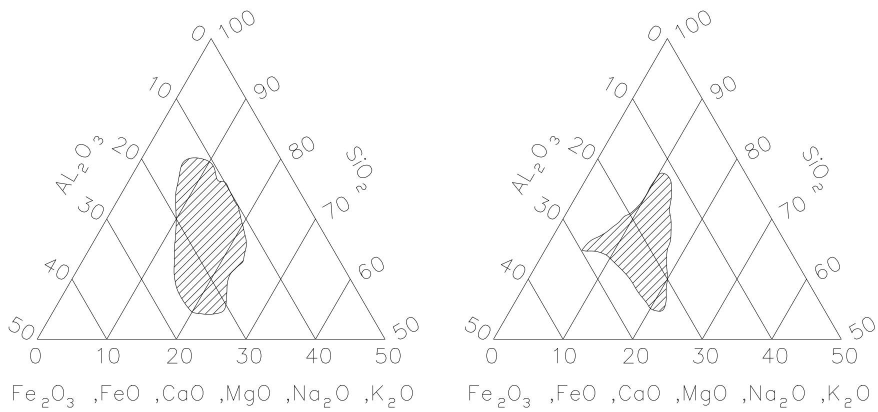


Figure 2. 1 - Chemical compositions zones of clays with expansive characteristics.
Source: COUTINHO (1998).

In Brazil, the production of expanded clay is accomplished by a single manufacturer and it is produced, mainly, for its use in the textile industry (the stonewashing of jeans) and for ornamentation (decoration of gardens).

Knowledge of the physical, chemical and mineralogical characteristics of the expanded clay are of great importance for the construction industry.

The aim of this work is to characterize the expanded clay available in the market, seeking its best specification and use for production of light concretes, since few data on this material exist.

2.2 EXPERIMENTAL PROCEDURE

2.2.1 Physical characterization

In the physical characterization of the expanded clay, it was evaluated the particle size distribution, the bulk density, the absolute specific gravity and the aggregate's absorption of water. The particle size analyses were accomplished according to NBR 7217 [10]. The unitary mass was determined according to the determinations of NBR 7251 [11]. The absolute specific gravity was obtained by helium picnometry. For the accomplishment of this study, the material was ground with the purpose of exposing the closed pores (isolated), so that the measured volume would only corresponded to the volume of the solid, excluding the pores of the sample. The water absorption content was obtained by the method of the NBR 9776 [12] and the evolution of the aggregate's absorption was evaluated during several intervals of time.

2.2.2 Microstructural characterization

Chemical, mineralogical and morphologic analyses were accomplished for the characterization of the expanded clay's microstructure, plus a thorough evaluation of the porosity. In the chemical characterization the methodology used is described in Table II.1.

Table II. 1 – Techniques of chemical analysis of expanded clay.

Component	Test Method
Ca, Mg	Volumetry – EDTA
Si	Gravimetry, HCl digestion.
Al, Na, K	Atomic Absorption Espectrometry, equipment AAnalyst 300, Perkin-Elmer.
Fe	Volumetry, by oxi-reduction - $K_2Cr_2O_7$.
C	Combustion analysis – Infrared detection, equipment CS-244 - LECO
LOI	Loss on ignition at 1000ºC

In the mineralogical characterization, the main present crystalline phases in the sample of expanded clay were determined using X-ray diffraction (XRD). A PHILIPS difratometer, model PW-3710 was used (radiation Cukα, current of 30 mA and tension of 40 kV, scanning with step of 0,06 and time of collection of 1,0 s/step). For the analysis of the crystalline phases, the values of "d" (the interplanary distance) were used with the approach of 0,01 Å [13].

The morphologic analysis and the elementary chemical analysis, of the phases present in the expanded clay, were obtained by the scanning electron microscopy (SEM) with an analyzer of X-ray by energy dispersive spectrometry (EDS). A PHILIPS, model JSM-80 microscope was used. Some grains of the analyzed sample presented the intern surface exposed, probably, due to the production process or to the transport. The images were obtained by secondary electrons, of the exposed intern surface and of the exposed surface of the grains, the samples being metallized with carbon film.

The apparent porosity of the sample was determined using mercury intrusion porosimetry. This technique is adapted to evaluate pores with diameters between 0,04 and 300 μm. The analysis was accomplished being considered the volume of the grains of the sample in the form of aggregates. Aggregates with dimension of 9,5 mm were chosen, as this dimension represents the greatest part of the particle size distribution of the expanded clay studied in this work.

2.2.3 Compressive strength test

The resistance of conventional aggregates as the calcareous crushed rock is obtained through the extraction of specimens of the rock and their axial compression rupture. Due to the great difficulty for obtaining specimens of expanded clay, since this material is produced industrially, and to the lack of a reliable method for evaluation of the aggregate's resistance, it has been done a qualitative evaluation, from the comparison among to the compressive strength of the concrete with calcareous crushed rock and of the concrete produced with aggregate of expanded clay.

For the evaluation of the mechanical performance of the concretes three different mixture proportions were adopted with estimate compressive strength of 20, 25 and 30 MPa, for the conventional concrete (reference) and for the lightweight aggregate concrete. The resistances to the axial compression analyses were done in agreement with NBR 5739 [14]. Specimens of concrete (diameter of 10 cm and height of 20 cm) were broken up at 3, 7 and 28 days old.

2.3 RESULTS AND DISCUSSION

2.3.1 Particle size distribution

Table II.2 presents the results of the particle size distribution analyses of the expanded clay aggregate.

Table II. 2 – Particle size distribution analysis of the expanded clay.

Size (mm)	Material retained (g)	Cumulative retained (%)	Cumulative passing (%)
19	0	0	0
12.5	433	9	9
9.5	2553	51	60
6.3	1520	30	90
4.8	393	8	98
Pan	100	2	100
Total	5000	100	
Maximum dimension characteristic (mm)		19	
Fineness modulus		6.48	

Based in the particle size analysis of the expanded clay, Table II.2, it can be observed that the expanded clay possesses maximum dimension characteristic of 19 mm. It is impossible to classify the particle size distribution of this coarse aggregate according to the specifications of the NBR 7211 [15], because the percentages accumulated retained in the sieve are not compatible with the particle size limits assigned in this norm.

2.3.2 Bulk density

In Table II.3 the results of the bulk density, absolute specific gravity mass and the absorption of the expanded clay used in this work are presented.

Table II. 3 – Bulk density, absolute specific gravity and absorption of the expanded clay.

Properties	Expanded clay				
Bulk density (kg/m^3)	460				
Absolute specific gravity (kg/m^3)	2570				
Water absorption by total immersion (%)	Time				
	5 min	15 min	30 min	60 min	24h
	15	15	20	25	30

The bulk density is in the zone between 300 kg/m³ and 650 kg/m³, corresponding to the expanded clay produced in rotative oven. The absolute specific gravity found presented in the Table II.3 approaches the amount of the real specific gravity of the raw material, because when ground, the porous matrix of the expanded clay no longer existed. This way, the larger the expanded clay aggregate, the bigger the intrinsic porosity of the material will be, resulting in a smaller bulk density. According with the results presented in Table II.3, it can be verified that the expanded clay presents high absorption of water in relation to conventional aggregates. This elevated absorption of water is related to the porous structure of their grains. It was verified that during the interval of 24 hours the absorption of water was not stabilized.

2.3.3 Mercury intrusion porosimetry of the expanded clay

In Table II.4 the results of the mercury intrusion porosimetry analyses are presented. The data show that the expanded clay has a high apparent porosity, which corroborates to the aggregate's high absorption

Table II. 4 – Results of the mercury intrusion porosimetry.

Sample weight (g)	Mercury Intrusion volume (ml/g)	Total pores area (m^2/g)	Average pores diameter (μm)	Apparent Porosity (%)
1.48	0.17	3.11	0.22	18.54

In Table II.5 the results obtained in the chemical analysis of the expanded clay are shown in the form of their respective oxides. The constituent's contents (chemical limits) for the clay to have expansible characteristics [2] are also listed in this table. Those limits should not be surpassed, because the clay would not melt in a temperature sufficiently low, or it would melt into an insufficiently viscous mass [2].

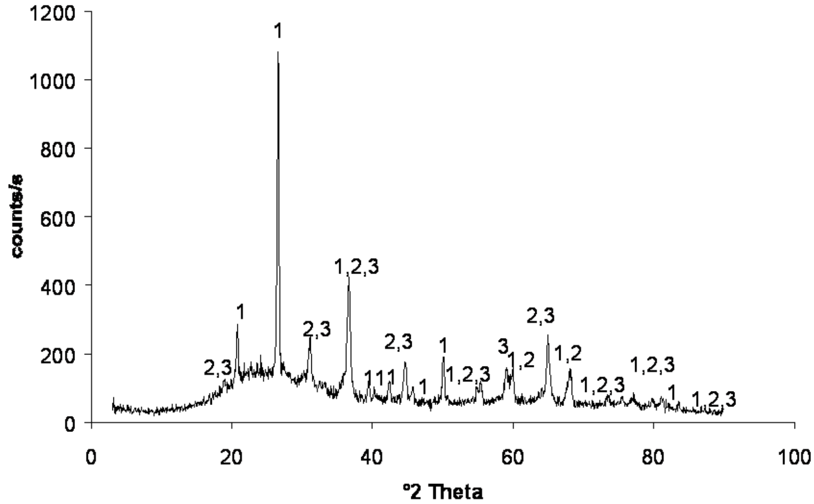
Table II. 5 – Chemical analysis of expanded clay.

Oxides	Chemical analysis (%)	Chemical limits (%)
SiO_2	63,35	50 a 65
Al_2O_3	11,68	16 a 20
Fe_2O_3	10,48	5 a 9
K_2O	4,32	1,5 a 4,5
Na_2O	0,39	alkalis content
MgO	3,68	1,5 a 3,5
TiO_2	0,42	-
CaO	0,25	1 a 4
S	0,02	0 a 1,5
LOI	0,81	6 a 8

By the results shown in Table II.5, it is observed that, in general, the chemical composition of the sample is within the zone determined for clays with expansible characteristics.

2.3.4 X - ray diffraction (XRD)

In Figure 2.2 the diffratogram and the main chemical phases of the expanded clay are presented, such as: silica (SiO_2) in the morphologic form of α-quartz; silicate of magnesium ($Mg(SiO_4)$) and oxide of aluminum and magnesium ($MgAl_2O_4$) in the spinelium form.



1- SiO_2 - Silicon (α-Quartz);
2- $Mg(SiO_4)$ - Magnesium Silicate;
3- $MgAl_2O_4$ - Magnesium Aluminum Oxide.

Figure 2. 2 – X - ray diffraction of the expanded clay.

It is observed in the diffratogram an elevation of the base line between, approximately, 15° and 40° indicating the presence of amorphous phases in the expanded clay studied.

2.3.5 Scanning electron microscopy (SEM) - expanded clay

In Figure 2.3 images obtained by SEM are presented, illustrating the morphology of the expanded clay. It was verified that the external surface of the expanded clay presents roughness texture (Figure 2a and 2c) than the internal surface of the sample (Figure 2b and 2d). It can be seen that the internal surface presents larger amount of pores, with interconnectivity. The largest porosity of the internal surface is related to the appearance of bubbles of gases originated in the process of production of the expanded clay.

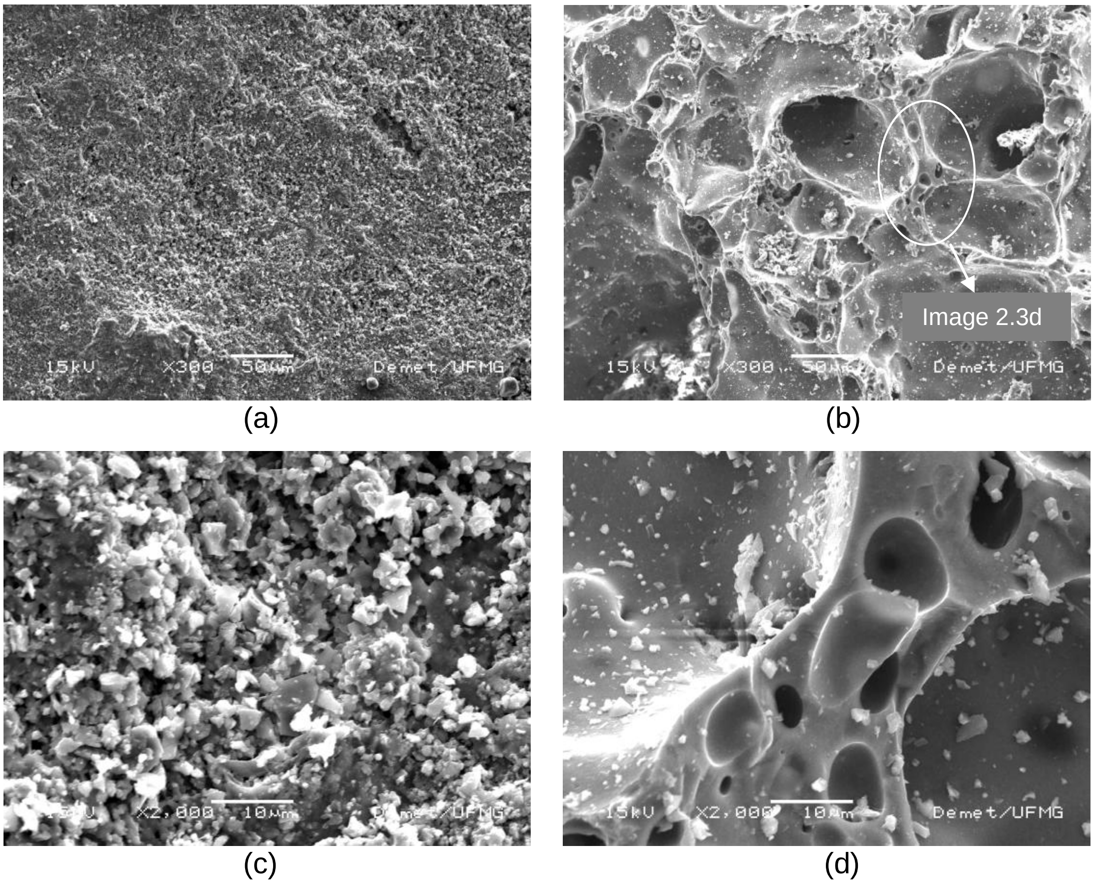


Figure 2. 3 – SEM images of expanded clay (a) external surface (300X); (b) internal surface (300X); (c) external surface (2000X); (d) internal surface (2000X).

2.3.6 Chemical analysis

Table II.6 presents the elementary chemical composition, in the areas of the images 2(a) and 2(c), obtained by EDS.

Table II. 6 – Average chemical composition in the analyzed areas EDS.

Oxides	Internal surface (%)	External surface (%)
O	45.4	46.9
Si	24.8	26.4
Al	10.4	12.4
Fe	9.4	5.6
K	5.1	4.1
Mg	2.4	1.8
Ti	0.8	0.8
Na	0.6	0.5
Ca	1.0	1.6

The expanded clay basically presents silicon, aluminum and iron, in its chemical composition. In the XRD analysis, the diffratogram of the sample presents an amorphous halo, suggesting the presence of amorphous phases, formed during the process of production of the expanded clay.

2.3.7 Compressive strength

The Figure 2.4 presented the results of compressive strength of the concretes with conventional aggregate and expanded clay, at 28 days old.

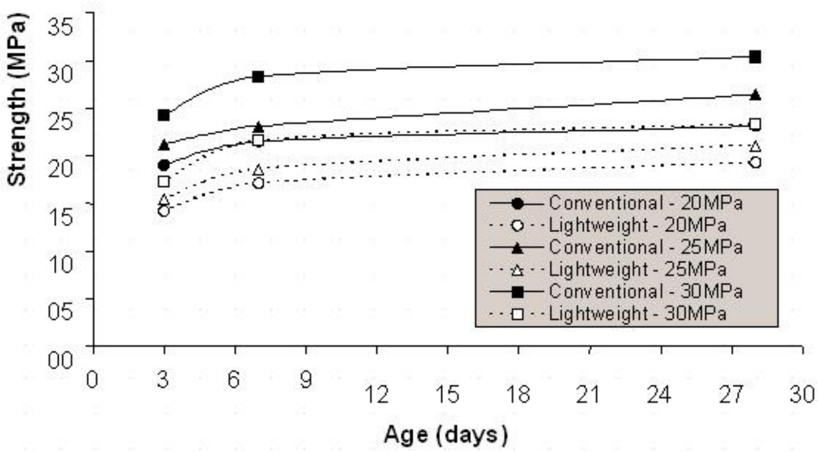


Figure 2. 4 – Compressive Strength of concretes.

The lightweight concrete presented a decrease in the compressive strength in relation to the reference concrete for all mixture proportion. This behavior can be associated with the lower strength of the expanded clay aggregate in relation to the limestone aggregate, what promote a reduction of the compressive strength in the lightweight concrete.

2.4 CONCLUSÕES

The expanded clay studied presents maximum dimension characteristic of 19 mm. The bulk density is in the area between 300 kg/m³ and 650 kg/m³, corresponding to the expanded clays produced in rotative oven.

The expanded clay presents high porosity in relation to the conventional aggregates, due to the porous structure of their grains, which also increases its absorption of water. This elevated absorption of water, when not foreseen, can be harmful to the concrete, reducing its workability. Besides, some of the water necessary for the hydration of the cement composition will be absorbed by this aggregate, possibly reducing the mechanical resistance of the concrete. As a solution, is recommended the aggregate's saturation, pre-moisturizing or the correction of the content of water used in the dosage of the concrete.

The expanded clay basically presents silicon, aluminum and iron, in its chemical composition. In the XRD analysis, the diffratogram of the sample presents an amorphous halo, suggesting the presence of amorphous phases, formed during the process of production of the expanded clay.

We verified that all of the mixture proportion of the lightweight concrete, presented resistance decrease in relation to the reference concrete. We can conclude that the expanded clay possesses smaller compressive strength in relation to the calcareous crushed rock.

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CAPÍTULO 3 - Compressive Strength and Modulus of Elasticity Behavior of the Lightweight Concrete with Expanded Clay Aggregate

Note: To be submitted to the International Conference on Non-Conventional Materials an Technologies IC - NOCMAT 2008.

Authors: Weber Guadagnin Moravia, Adriana G. Gumieri, Wander L. Vasconcelos.

Abstract

Nowadays the lightweight concrete has been used in a larger scale for structural purposes and for reduction of the self weight of structures. Specific gravity, compressive strength, strength/weight ratio and modulus of elasticity are important factors in the mechanical behavior of the structures. This work studies these properties in lightweight aggregate concrete (LWAC) and normal-weight concrete (NWC), comparing them. The specific gravity was evaluated in fresh and hardened state. In the evaluation of the compressive strength four mixture proportions were adopted. For each proposed mixture proportion, cylindrical specimens were molded for both concretes and tested at ages of 3, 7 and 28 days. The modulus of elasticity of the NWC and LWAC was analyzed by static, dynamic and empiric methods. The results show a larger strength/weight ratio for LWAC although this concrete had presented smaller compressive strength.

Keywords: lightweight concrete, compressive strength, modulus of elasticity.

3.1 INTRODUCTION

The low relation strength-weight of the concrete, when compared with the steel, constitutes a disadvantage of that material when applied in the construction. To improve this relation we can reduce the specific gravity of the concrete or increase its strength. In the last decades, a reduction of the specific gravity of the concrete has been obtained, successfully, through the lightweight concrete use.

There are three types of lightweight concrete with specific methods for the reduction of their densities. The aired concrete or cellular is based on the introduction of empty holes formed by bubbles of gas inside the mass of that concrete. The concrete without fines is based on the absence of the fine aggregate in that concrete, so that a great amount of empty holes is formed. The lightweight aggregate concrete (LWAC) is obtained using a porous aggregate of low specific gravity, replacing the conventional aggregate [1].

The LWAC is often used, in relation to the other types of lightweight concrete, due to the great variety of aggregates with low density, making possible the production of concretes with different properties. Besides, LWAC possesses larger mechanical resistance when compared to the other types of lightweight concrete, allowing its use as structural concrete.

The expanded clay can be used as aggregate in the production of lightweight concrete, due to its low density. This aggregate is produced from some clay types, that expand during thermal treatment, due to the decomposition of some of their components and the consequent formation of gases that are kept in the viscous mass of the clay during the coalition [1,2]. In the growing shortage of conventional aggregates it represents an important alternative for the production of concretes.

This work evaluates the mechanical properties of the lightweight concrete produced with expanded clay, analyzing its compressive strength, modulus of elasticity, and the efficiency factor (mechanical resistance x density).

3.2 EXPERIMENTAL PROCEDURE

In the present work an expanded clay characterized by [3] was used as coarse aggregate in LWAC, and a limestone with a particle size distribution compatible to that observed in the expanded clay was used in normal-weight concrete (NWC). The fine aggregate was washed natural quartz sand, presenting medium-fine particle size distribution. This size was chosen as it provides smaller segregation of the expanded clay in the LWAC. The cement used in the concretes was a Portland cement CPV, corresponding to the ASTM C 150, that has as its main characteristic high initial strength. This cement type was chosen because for not containing mineral admixtures, as blast furnace slags or pozzolans.

3.2.1 Mixture proportions method

The concrete mixture proportions were determined according to the IPT/USP method [4]. This method is based on the obtaining of concrete proportions which provide a requested consistence and an average compressive strength to (fcj) at j days of age. It was used as dosage parameter a mortar content of 60% for both concretes. A pre-moisturizing of the expanded clay was conducted for 5 minutes, as recommended in [5], to partially compensate the tax of absorption of the lightweight aggregate, minimizing the problems of workability of the concrete and, at the same time, reducing the excess of water in the mixture, which would implicate in the reduction of its mechanical resistance.

3.2.2 Compressive strength and density analysis

In the evaluation of the compressive strength four mixture proportions were adopted. For each proposed mixture proportion, cylindrical specimens were molded (10 cm of diameter and 20 cm of height) for both concretes, in agreement with NBR 5738 [6]. The specimens were cured in a moist room and tested at the ages of 3, 7 and 28 days, in agreement with NBR 5739 [7], corresponding to the standard American ASTM C 39.

After the molding, the density was measured in the fresh state for NWC and for LWAC. The density of the concrete in the hardened state was obtained by the relationship between the mass and the volume of the specimen at the ages of 3, 7 and 28 days.

3.2.3 Modulus of elasticity analysis

The static modulus of elasticity, corresponding to the secant modulus, was obtained for both concretes. The secant modulus is determined by the inclination of a drawn straight line of the origin to a point of the stress x deformation curve corresponding to 40% of the rupture stress in cylindrical specimens, in agreement with the norm NBR 8522 [8], corresponding to the standard American ASTM C 469. For each proportion and type of concrete 3 specimens were analyzed at 28 days of age.

The dynamic modulus of elasticity of the concretes (modulus of Young), was determined from the measure of the resonance frequency (traverse) of specimens of NWC and of LWAC, in agreement with American Standard ASTM C 215. For the determination of that modulus, it was used, for each proportion, 3 cylindrical specimens (10 cm of diameter and 20 cm of height), at 28 days old.

The modulus of elasticity was also determined, from the empiric formula, suggested by the commission ACI 318 [9], specified below. The Equation 3.1 relates the modulus of elasticity with the compressive strength of the concrete and it was chosen among others because it also takes into consideration the density of the material.

$$E_c = 43 \times 10^{-3}\ \rho^{1,5} \sqrt{f_c} \qquad \text{(Equation 3.1)}$$

Were:

E_c - modulus of elasticity (GPa);
f_c - compressive strength (MPa);
ρ - density (kg/m³).

3.3 RESULT AND DISCUSSION

3.3.1 Mixture proportions

Table III.1 shows the proportions, the consumption of the materials by cubic meter of concrete, and the results obtained in the slump test.

Table III. 1 – Proportions and consumption of the materials by cubic meter of concrete.

Stimated Compressive Strength (MPa)	Concrete	Mix Proportion (weight)	Portland Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	W/C	Slump (mm)
20	NWC	1:3.21:2.79	373	1197	1042	0.63	85
	LWAC	1:3.21:0.79			293		75
25	NWC	1:1.99:2.24	465	925	1042	0.55	140
	LWAC	1:1.99:0.63			293		165
30	NWC	1:1.40:1.80	579	811	1042	0.48	165
	LWAC	1:1.40:0.51			293		170
40	NWC	1:1.10:1.59	655	720	1042	0.41	174
	LWAC	1:1.10:0.45			293		180

In general, the reduction of the slump of LWAC was larger than the obtained for NWC. The slump increased with the increase of the estimate resistance due to the greater cement consumption and, consequently, larger amount of paste involving the aggregates. A bigger difference among the values of consistence of the two concrete types was expected, due to the greater influence of gravity in the conventional aggregates. However, the values obtained in the slump test for LWAC approached the values found for NWC. The consistence increase for the LWAC can be attributed to the round form of the expanded clay, providing larger workability to the concretes. It is important to emphasize that this aggregate's pre-moisturazing contributed to the improvement of the consistency, avoiding the absorption of the necessary water to the workability of the concrete.

3.3.2 Density of the concrete in the fresh and hardened state

In Table 3.2 the NWC and LWAC density values are presented. According to the standard ASTM C 330, the specific gravity of the LWAC structural concrete, in the dry state, should not exceed than 1.850 kg/m^3 and it usually possesses values among 1.400 and 1800 kg/m^3. The lightweight insulating concrete (without structural function) usually possesses smaller specific gravity than 800 kg/m^3. In way, the LWAC analyzed in this study can be classified as structural, regarding the specific gravity values they present. It was also observed that there is directly proportional relationship between the specific gravity and the compressive strength of the concretes.

Table III. 2 – Density of the analized concrete.

Density of the concretes (kg/m³)					
Mixture Proportions (MPa)	Concrete	Fresh	Age (days)		
			3	7	28
20	NWC	2312	2325	2293	2293
	LWAC	1617	1571	1635	1603
25	NWC	2327	2336	2327	2325
	LWAC	1621	1604	1620	1615
30	NWC	2350	2340	2352	2386
	LWAC	1634	1611	1618	1622
40	NWC	2431	2346	2367	2410
	LWAC	1652	1614	1644	1645

3.3.3 Compressive strength

The results of the axial compressive strength of the concretes, evaluated at the ages of 3, 7 and 28 days, are displayed in Table 3.3.

Table III 3 - Axial compressive strength of the concretes.

Stimated Compressive Strength (MPa)	Concrete	Compressive strength (MPa)								
		3 days	Mean	S_d	7 days	Mean	S_d	28 days	Mean	S_d
20	NWC	18.2	18.6	0.4	20.0	20.6	0.8	23.1	22.7	0.6
		18.5			20.2			22.0		
		19.0			21.5			23.0		
	LWAC	12.5	13.5	1.4	17.1	16.3	1.2	15.5	17.6	1.9
		8.7*			14.9			19.3		
		14.5			17.0			18.0		
25	NWC	21.2	20.9	0.4	22.3	22.4	0.6	26.3	26.0	0.7
		21.0			21.9			26.4		
		20.4			23.1			25.2		
	LWAC	14.9	15.1	0.3	16.6	17.6	1.0	18.4	18.9	1.0
		15.5			18.6			18.2		
		15.0			17.5			20.1		
30	NWC	24.3	24.0	0.4	26.1	27.1	1.1	28.6	28.1	2.5
		23.6			28.3			25.3*		
		24.0			26.8			30.4		
	LWAC	13.4	15.4	2.7	12.3*	19.9	2.4	20.5	21.8	1.4
		17.3			18.2			21.7		
		9.0*			21.6			23.3		
40	NWC	32.8	33.4	2.9	35.9	35.1	1.1	46.5	46.6	3.5
		30.8			34.3			43.2		
		36.5			44.6*			50.2		
	LWAC	28.4	27.5	0.7	28.6	29.2	0.7	30.2	33.4	3.1
		27.3			28.9			36.2		
		26.9			30.0			34.0		

* Values not taken into account. S_d – Standard deviation

The Figure 3.1 presents the results of axial compressive strength according to the age of the specimens for concretes analized.

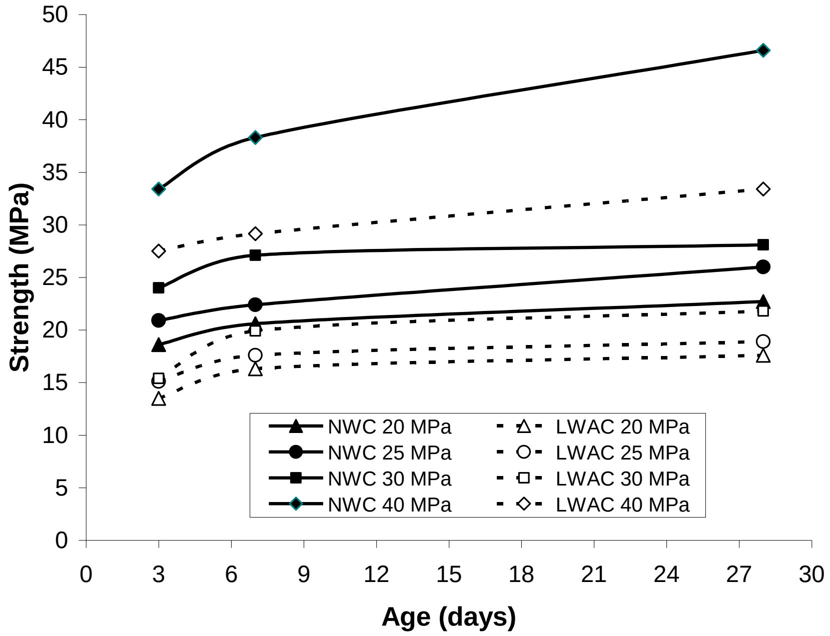

Figure 3. 1 - Compressive strength of concretes.

The LWAC presented a reduction around 22% to 28% of the compressive strength in relation to the NWC. It was noticed that decrease of the resistance of the LWAC is larger for the concrete with an estimated compressive strength of 40 MPa. The largest strength decrease in this mixture proportion can be explained by the smallest strength of the lightweight aggregate. According to the American standard ASTM C 330, the lightweight structural concrete should have compressive strength larger than 17 MPa at 28 days of age, determined by the rupture of the axial compression of the cylindrical specimen. However, the Brazilian standard NBR 6118 [10], specifies minimum values of 20 MPa for structural concretes, not mentioning the case of the lightweight concrete. It is observed that, in spite of the decrease of mechanical strength, the lightweight concrete reached the strength specified by the American and Brazilian standards, this resistance being under the specifications only for the concrete dosed for 20 and 25 MPa.

3.3.4 Efficiency factor and stress-strain graphics

The Figure 3.2 displays the efficiency factor of the NWC and of the LWAC for an estimated compressive strength of 40 MPa, obtained from the ratio between the mechanical resistance and the density of each concrete. It was observed that LWAC had a better performance, because, although it has presented smaller compressive strength than NWC, its density decreased in larger proportion, and the result obtained for the efficiency factor at 28 days of age, was 8% larger in relation to NWC. As, for most of the materials, there is a relationship directly proportional between the mechanical resistance and the density, that behavior of LWAC indicates that there was an improvement of its properties, probably caused by physical or chemical phenomena in the interior of that concrete.

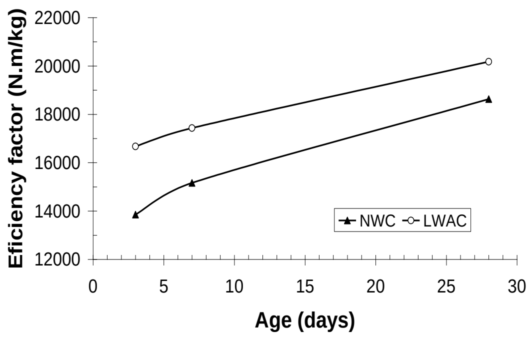

Figure 3. 2 - Eficiency factor of concretes

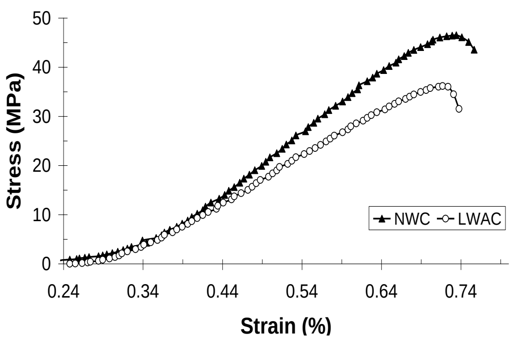

Figure 3.3 - Strain/stress graphic of concretes

The Figure 3.3 shows the stress-strain curves of the concretes analyzed for an estimated resistance of 40 MPa. It was observed that LWAC presented a behavior similar to NWC standing out by its smallest compressive strength and by its smallest modulus of elasticity.

3.3.4 Static and dynamic modulus of elasticity

In Table 3.4 the results of the static and dynamic modulus of elasticity are presented for specimens of NWC and of LWAC, as well, the calculation modulus using empiric equation.

Table III. 4 – Static and dynamic modulus of elasticity of the analyzed concretes.

Strength (MPa)	Specimes	Modulus of elasticity (GPa)		
		Estatic	Dinamic	Empiric
46.6	NWC	25.1	29.1	34.7
33.4	LWAC	16.0	18.2	16.6

It can be observed, in Table 3.4, the results of the estatic, dynamic and empiric modulus of elasticity. The last one it was calculated using Equation 3.1. The values obtained for the static modulus of elasticity were smaller in relation to the found in the other methods, this reduction consisting of 14% for NWC and of 12% for LWAC when compared to the dynamic modulus. That difference can be justified by the greater precision of the method used in the determination of the static modulus of elasticity. As seen previously, this method determines the modulus from the stress x strain diagram, being, therefore, more representative than the others. The values obtained for the static modulus of elasticity of LWAC were in the area between 15 GPa and 17 GPa, being in the average third of the values obtained for NWC, as results found by other authors [1]. That result evidences the greatest capacity of LWAC to absorb small deformations as the ones caused by retraction efforts, which can reduce the internal tensions and reduce the micro-crack formation in that concrete, in relation to NWC.

3.4 CONCLUSIONS

The LWAC presented a compressive strength smaller than the NWC, for the same mixture proportion with an estimated compressive strength of 40 MPa. The largest strength decrease in this mixture proportion can be explained by the smallest strength of the expanded clay when compared with limestone aggregate. It can either be observed that, the LWAC analyzed in this study can be classified as structural concrete, regarding the density and compressive strength values they present.

Although it has presented smaller values to compressive strength, the LWAC presented a better efficiency factor in relation to the NWC. This behavior of LWAC indicates that there was an improvement of its properties, probably caused by physical or chemical phenomena in the interior of that concrete.

The values obtained for the static modulus of elasticity of LWAC were in the average third of the values obtained for NWC. This result indicate the greatest capacity of LWAC to absorb small deformations as the ones caused by shrinkage, which can reduce the internal stress, the formation of micro-crack, and increase the service life of that concrete, in relation to NWC.

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CAPÍTULO 4 - Evaluation of the Thermal Conductivity, Specific Heat and Thermal Diffusivity of the Lightweight Concrete with Expanded Clay Aggregate

Note: To be submitted to the Journal of Thermal Analysis and Calorimetry

Authors: Weber Guadagnin Moravia, Adriana G. Gumieri, Alexandre de C. Pereira
Moacir Alexandre de Souza Andrade, Wander Luiz Vasconcelos.

Abstract

Concretes exposed to thermal variations or high temperatures can present alterations in their properties, committing their efficiency and, consequently, their durability. The mechanical properties and durability of concrete are affected by factors such as mixture proportion, porosity and changes of temperature. Usually, lightweight concrete presents better performance than normal-weight concrete when exposed to thermal variations. In this work, the microstructure of expanded clay and limestone aggregate, lightweight concrete with expanded clay (LWAC) and normal-weight concrete (NWC) was investigated through water absorption and mercury intrusion porosimetry tests. Thermal conductivity, specific heat and thermal diffusivity assays were done to evaluated thermal properties of both concretes. It was observed a better behavior for LWAC in compare with NWC when submit a thermal gradient.

Keywords: lightweight concrete, thermal conductivity, specific heat, thermal diffusivity.

4.1 INTRODUCTION

Concretes exposed to thermal variations or high temperatures can present alterations in their properties, committing their efficiency and, consequently, their durability. However, some concrete types are more resistant to thermal stress than the NWC. Researches approaching that theme aid in the determination of the properties that contribute to a larger efficiency of the concrete when submitted to thermal gradients.

The mechanisms of deterioration of the concrete due to thermal variations consist of the appearance of differential internal stress that will promote and to spread fissures, forming rupture plans or a preferential net of connectivity among the pores, increasing the permeability of the concrete and making it more susceptible to attack of aggressive agents.

The determination of such thermal properties as the thermal conductivity, the specific heat and the thermal diffusivity are necessary parameters to understand the behavior of the concrete when submitted to thermal variations.

4.1.1. Thermal conductivity

Thermal conductivity is the measure of the capacity of a certain material for conducting heat. The coefficient of thermal conductivity, K, can be defined as the reason between the flow of heat transmitted by the material’s unitary thickness, between two faces of an unitary area, and the temperature gradient [1]. The thermal conductivity of the concrete is determined, mainly, by its porosity and its saturation degree and influenced by the relative proportions of the aggregates and the cement paste in the concrete [2]. The thermal conductivity is an important property for the determination of the penetration rate (flow) of heat inside the concrete that it will contribute to the appearance of thermal stress [3].

4.1.2 Specific heat

The specific heat is defined as the reason between the amount of necessary heat to increase 1° (one degree) an unit of weight of the material, and the amount of necessary heat to increase 1° (one degree) the same weight of water [1]. Researches indicate that the specific heat of the LWAC slightly differs from the specific heat of the NWC to room temperature, but it increases considerably at temperatures close to 600°C [4]. The specific heat is associated to the thermal stability or volume of the concrete.

4.1.3 Thermal Diffusivity

In concretes, the thermal diffusivity represents the speed of which temperature variations happen in its interior. Therefore, it is an indicator of the easiness of which the concrete can suffer thermal stress becoming susceptible to their effects. For NWC, the typical values of thermal diffusivity are located in the interval between 0.002 and 0.006 m^2/h, depending on the aggregate type [5]. Due to the influence of the humidity contents on the thermal properties of the concrete, the thermal diffusivity should be maintained in the concrete bodies with humidity contents equal to the existent in the real structure.

4.2 EXPERIMENTAL PROCEDURE

The bulk density of the expanded clay used as the lightweight aggregate in this work equal to 460 kg/m^3 [6]. A limestone coarse aggregate was used in the reference concrete. In this case, a particle size distribution compatible to that observed in the expanded clay was obtained. In both concretes the fine aggregate was washed natural quartz sand, presenting medium-fine particle size distribution. This size distribution was chosen as it avoids segregation of the expanded clay in the LWAC. The water absorption of the expanded clay, and its evolution at different time intervals, was evaluated following the method described in [7].

The apparent porosity of the expanded clay, limestone aggregates and concretes were established using mercury intrusion porosimetry. Aggregates with dimension of 9.5 mm were chosen, as it represents the major part of the coarse aggregate distribution studied. For the porosity concrete tests, cylindrical specimens (diameter of 20 mm and height of 25 mm, using aggregates with dimension of 5 mm) were tested at 28 days.

Tests were accomplished to evaluate the thermal properties as the thermal conductivity, the specific heat and the thermal diffusivity of the concretes.

4.2.1 Thermal conductivity test

The thermal conductivity of the concretes was evaluated using a Quick Thermal Conductivity Meter (QTM-D3) equipment (Figure 4.1). Measurement precision is ± 5% of reading value. That device measures the thermal conductivity automatically processing the data generated starting from a probe coupled in a plane face on the specimens. This device is based on the mathematical calculation of the transient heat that it goes by the probe wire in contact with the specimens. Cylindrical specimens were studied (diameter 10 cm and height 20 cm) on the 28th day old, for concretes with compressive strength of 25, 30 and 40 MPa.

Figure 4. 1 - Thermal conductivity equipment.

4.2.2 Specific heat test

The evaluation of the specific heat of the concretes was accomplished following the procedures [8]. Two cylindrical specimens were shaped (20 cm diameter and 40 cm height, with a central hole of 38 mm diameter) for concretes with compressive strength of 40 MPa. The equipment used is constituted of a calorimeter and of digital quartz, precision thermometer. The heat was supplied by an electric resistance put inside the central hole of the specimens, which heated up the distilled water that involved it. The amount of heat supplied to elevate the temperature of the concrete was determined by a wattmeter.

Once the specific heat of the concrete varies with the temperature, they were made three determinations, in different temperatures, for each specimen. In the methodology of the applied studies, it is not possible to measure the specific heat of the concrete in a condition other than the saturated, being so, it is necessary to correct the value of the specific heat found in this method for the desired humidity. As concretes exposed to room temperature present humidity contents between 10% and 20%, the obtained results were corrected for the humidity contents of 20%.

4.2.3 Thermal Diffusivity test

The thermal diffusivity of the concretes was obtained by Equation 4.1, which relates this thermal property to the thermal conductivity, the specific heat and the density of the concrete.

$$k = \frac{K}{c\rho} \qquad (Eq\ \ 4.1)$$

Where:

k = thermal diffusivity (m^2/h);

K = thermal conductivity (W/m·K or J/m·s·°C);

c = specific heat (J/kg·K);

ρ = density of the material (kg/m^3).

4.3 RESULTS AND DISCUSSION

4.3.1 Water absorption

Table IV.1 presents the results of the water absorption of the expanded clay. According to the results presented in Table IV.1, it is verified that the expanded clay presents high absorption of water in relation to the conventional aggregate, which is related to the porous structure of their grains. It was verified that, after 24 hours, the water absorption was not stabilized, as suggested in [9]. In spite of that, it was not necessary to continue with the saturation test, as a major part of the absorption was obtained within 60 minutes of immersion.

Table IV. 1 - Results of the water absorption of the expanded clay.

Period	5 min.	15 min.	30 min.	60 min.	24 h
Water Absorption (%)	15	15	20	25	30

4.3.2 Mercury intrusion porosimetry (MIP)

In Table IV.2, the results of the mercury intrusion porosimetry tests are presented for the limestone and expanded clay aggregate, NWC and LWAC. It can be observed that the lightweight aggregate presents a larger apparent porosity than the calcareous aggregates, what contributes to its high absorption. The expanded clay utilized in LWAC promotes a higher porosity in this concrete when compared with NWC. The thermal properties of LWAC are influenced by your porosity.

Table IV. 2 - Results of the porosimetry for the aggregates and concretes.

Samples	Apparent Porosity (%)
Limestone Aggregate	1.00
Expanded Clay Aggregate	18.54
NWC	10,60
LWAC	27.79

4.3.3 Thermal conductivity

In the Table IV.3 the values of the thermal conductivity of the concretes are presented for compressive strength of 25 MPa, 30 MPa and 40 MPa, on the 28th day.

Table IV. 3 - Thermal conductivity of the concretes.

Strength (MPa)	Concrete	Density (kg/m^3)	Mix Proportion (weight)	W/C	Slump (mm)	Mortar Content (%)	Fine Aggregate Content (%)	Thermal Conductivity (W/m·K)
25	NWC.	2293.0	1:1.99:2.24	0.55	140	57.2	47.1	2.679
	LWAC	1560.5	1:1.99:0.62	0.55	165	82.8	76.2	0.995
30	NWC.	2386.4	1:1.40:1.80	0.48	165	57.1	43.8	2.538
	LWAC	1622.3	1:1.40:0.50	0.48	170	82.7	73.7	1.131
40	NWC.	2409.8	1:1.10:1.59	0.41	174	57.0	40.9	2.127
	LWAC	1645.4	1:1.10:0.45	0.41	180	82.3	70.9	1.244

The thermal conductivity of the concrete is determined, mainly, by its porosity and its saturation degree and influenced by the relative proportions of the aggregates and the cement paste in the concrete [10,11]. The values obtained for the thermal conductivity of the NWC are in the interval between 1.4 and 3.6 W/m·K, as suggested in [5]. The results for the LWAC were 37%; 45% and 58% of the values obtained for the NWC, for the compressive strength of 25 MPa, 30 MPa and 40 MPa, respectively. That difference can be explained by the low thermal conductivity of the air present in the pores of the lightweight aggregate.

The thermal conductivity of the LWAC increased with the increase of the bulk density, according to the expected. However, that behavior was not observed for the NWC. Both concretes presented larger slump with the increase of the mechanical resistance, due to the reduction of small aggregate's content in the mix proportions, what contributed to the increase of the amount of water in the cement paste. The larger the water content present inside the pores of the concrete in the hardened state the lower will be the thermal conductivity for NWC. However, in LWC, an increase in the humidity content results in an increase of the conductivity. This can be explained by the smaller thermal conductivity of the air in comparison to the thermal conductivity of the water (present in the lightweight aggregate's pores) which is smaller than the half of the amount of the thermal conductivity of the cement paste [1].

The amount of thermal conductivity of the LWAC which was evaluated in this research came close to the obtained by Mindess [2] for cement pastes (1,0 to 1.5 W/m·K). Therefore, in the LWAC, possibly, there are smaller thermal stress between the aggregates and the cement paste in relation to the NWC, which contributes to a smaller fissuring index.

4.3.4 Specific heat

In the Figure 4.2 the obtained amount for the specific heat of the concretes according to the temperature for a humidity content of 20% is shown.

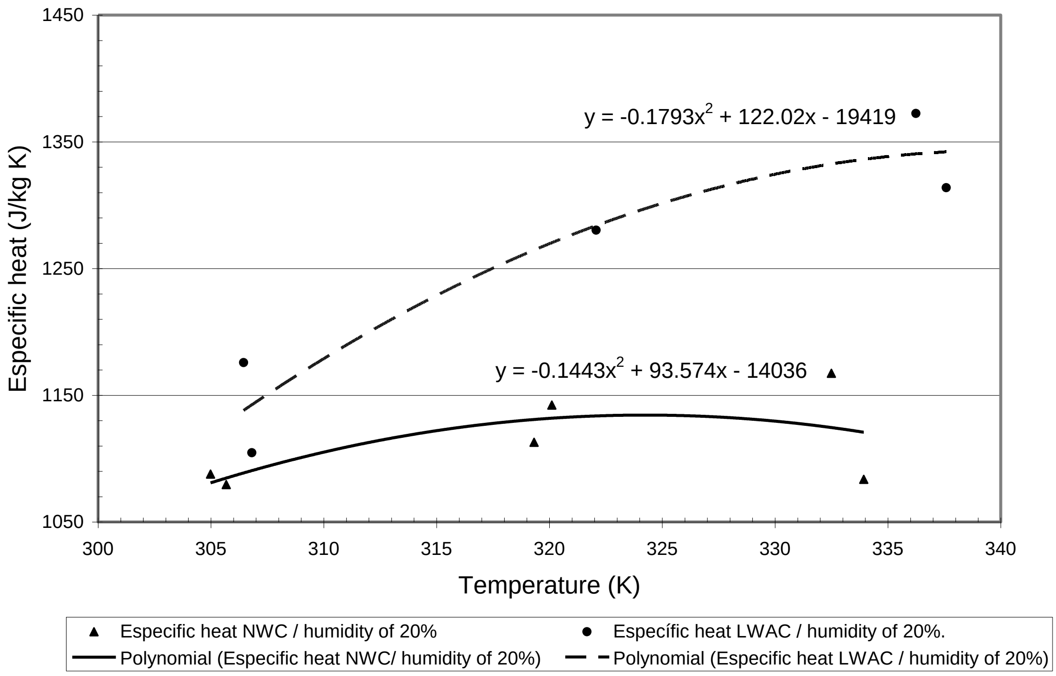

Figure 4. 2 - Curve of the specific heat of the concretes.

The specific heat for a temperature of 301 K (28 °C) was equal to 1056 and 1064 J/kg·K for NWC and LWAC, respectively. The result obtained for NWC is placed between 840 and 1170 J/kg·K suggested by Metha and Monteiro [12]. Usually, for temperatures between 293 and 303 K (20 e 30 °C), the amount of specific heat of the LWC differs slightly from the amount found for the NWC [1]. However, the growth rate of the specific heat for the LWAC increases as the temperature arises, proving its insulating characteristic.

4.3.5 Density of the concrete

The density of LWAC and NWC aged 3, 7 and 28 days, for estimated compressive strength of 40 MPa, is shown in Table IV.4. These values were used in the calculation of the thermal diffusivity. It was verified that there was an average reduction of 32% of the bulk density of the LWAC in relation to the NWC on the 28th day. This difference may be attributed to the substitution of the normal-weight aggregate (ρ = 1.638 kg/m^3) by the expanded clay (ρ = 460 kg/m^3). Table IV.5 shows the thermal diffusivity for the concretes, calculated by the Equation 4.1. On this calculation it was considered the results of thermal conductivity for an estimated strength of 40 MPa (Table IV.3), and the values of specific hate for a temperature of 301 K (Figure 4.2).

Table IV. 4 - Density of Concretes**.**

Density (kg/m3)				
Compressive Strength	Concrete	Age (days)		
		3	7	28
(40MPa)	NWC	2346.1	2367.3	2409.8
	LWAC	1613.6	1643.5	1645.4

4.3.6 Thermal diffusivity

Table IV. 5 - Thermal diffusivity of the concretes aged 28 days.

Concrete (40 MPa)	Density (kg/m3)	Thermal Conductiviy (J/m·h·K)	Specific Heat (J/kg K)	Thermal Diffusivity (m^2/h)
NWC	2409.8	9136.8	1056.4	0.0036
LWAC	1645.4	4071.6	1066.5	0.0023

It can be verified, by the Equation 1, that the thermal diffusivity of concretes are directly proportional to its thermal conductivity and inversely proportional to the product of the specific heat for the density. The specific heat of the concretes does not vary greatly at ambient temperatures close to 301 K (28 °C) and the thermal diffusivity depends mostly on the thermal conductivity and the density of concretes. For LWAC, the density and the thermal conductivity are minor when compared to NWC. This reduction is more significant for the thermal conductivity, resulting, consequently, in a smaller value of the thermal diffusivity in the LWAC. This factor represents a smaller rate of temperature variation along the time for LWAC.

4.4 CONCLUSIONS

The LWAC presented larger porosity than NWC, due to the expanded clay utilized as aggregate in the first one, what may have promoting an improve of the thermal properties of the LWAC.

The LWAC transfers less heat in relation to the NWC due the low thermal conductivity of the air present in the pores of the expanded clay. This difference reduces with the raise of the estimated resistance of the concretes.

The LWAC presented lower thermal diffusivity than the NWC. Otherwise, for temperatures between 293 and 303 K (20 and 30 °C), the specific heat of the LWAC differs slightly from the amount found for the NWC. That behavior of the LWAC contributes for a better thermal resistance in compare to NWC.

The great proximity between the thermal conductivity of the LWAC and of the cement paste, associated with the higher specific heat of the LWAC lead to the conclusion that the LWAC presents lower thermal stress, what results in a smaller cracking and contributes to a higher durability.

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CAPÍTULO 5 - Effects of the Increase of Temperature on the Physiochemical Transformations in the Microstructure of Lightweight Aggregate Concrete

Note: To be submitted to the Jounal of Thermal Analysis and Calorimetry.

Authors: Weber Guadagnin Moravia, Adriana G. Gumieri, Wander L. Vasconcelos.

Abstract

One of the most important requirements of the concrete is that it should be durable under certain conditions of exposure. This paper is concerned with the influence of the change of temperatures in the normal-weight concrete (NWC) and lightweight aggregate concrete (LWAC) behaviors as well as its durability when they are exposed to thermal gradient. It was used X-ray diffraction analyses in the coarse aggregates and in the concretes to determinate the main phase presents in these materials. To evaluate the effects of the increase of temperature and the microstructural transformation of the investigated concretes, were done thermal expansion tests and thermal analysis. The LWAC presented smaller thermal expansion and larger thermal stability in relation to the NWC.

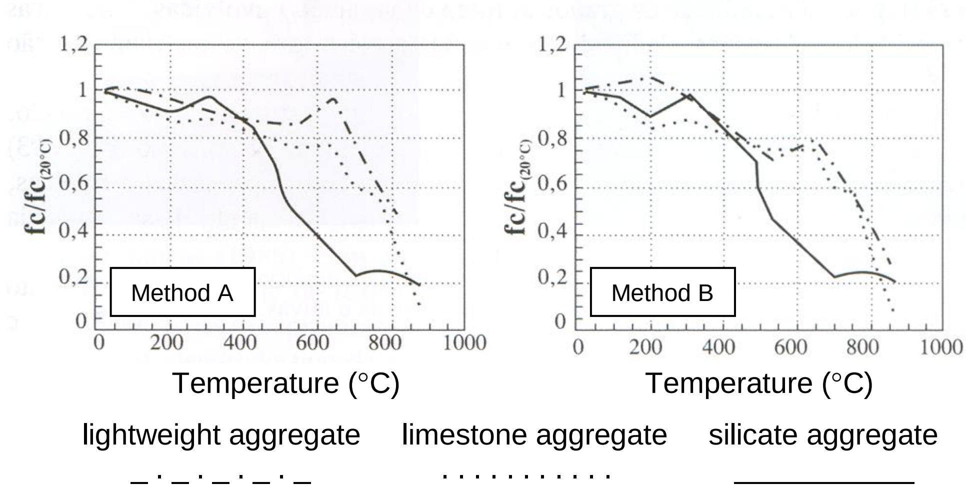
Keywords: lightweight concrete; thermal expansion; thermal analysis.

5.1 INTRODUCTION

Structural concrete possess excellent thermal resistance when compared to the metallic structures, and they present larger durability when submitted to higher temperatures due to their thermal properties. The study of the influence of the thermal properties in the durability of the concrete is very complex, as we are dealing with a heterogeneous material, constituted by different materials. However, that study is indispensable to predict the behavior of the concrete when submitted to temperature variations, facilitating, this way, its specification in structural projects and its application as refractory materials.

Lightweight concrete, in general, presents a better thermal performance when compared to the conventional concrete. The fact which can contribute to the increase of the durability of the structures that use that type of special concrete. The best thermal performance of the lightweight concrete is related, largely, to the porous structure and to the characteristics of the aggregates used.

Lightweight aggregates may have a strong influence in the mechanical behavior of the concrete to temperatures between 450 and 800 °C, contributing to a smaller relatively decrease compressive strength with respect to normal weight with those aggregates [1], as it can be seen in Figure 5.1.



(a) (b)

Figure 5. 1 - a) Influence of the three aggregate types in the compressive strength of the concrete under initial tension (Method A). b) Without initial tension (Method B).

Fonte: ABRAMS, (1971).

Thermal analyses can be accomplished to evaluate the physiochemical transformations in the microstructure of the concretes that may happen during changes of temperature. The effects of those transformations can be measured by analyses of thermal expansion seeking the development of more durable concrete structures.

5.1.1 Thermal analyses

The thermogravimetry (TG) is based on the study of the variation of the mass of a sample, resulting from a physical transformation (sublimation, evaporation, condensation) or chemical transformation (degradation, decomposition, oxidation) due to the temperature [2]. The Differential Thermal Analysis (DTA) is a thermal technique in which the temperature change is measured (endothermic or exothermic reactions) between the sample and an inert substance, when both are submitted to heating or cooling. These techniques are useful to assess the temperature range to which the elements could endure [3].

5.1.2 Thermal expansion

The thermal expansion coefficient is defined as the variation of the linear dimension by unit of length, due to a change of temperature. In the concrete, that coefficient is influenced by the coefficients of the coarse aggregate and of the mortar that constitutes it. Due to the differences between the aggregate and the mortar coefficients of thermal expansion, thermal variations may cause a differential expansion in the dimensions of these phases, resulting in the rupture of the bond among the grains of the aggregates and of the paste that involves them, originating micro-cracks that will commit the performance of the concrete [4,5]. The maximum difference between the coarse aggregate's coefficient and the coefficient of the mortar should not exceed 5 x 10^{-6}/°C so that effect is not considered intense [5].

Not all aggregates possess minerals with isotropic characteristics, therefore aggregates with lower thermal expansion coefficient usually produce more stable concretes. The thermal expansion coefficient for cement pastes varies from 11 to 16 x 10^{-6}/°C, for mortars the limits are between 8 and 12 x 10^{-6}/°C, while for limestone aggregates, that coefficient is around 26 x 10^{-6}/°C [6,7].

5.2 EXPERIMENTAL PROCEDURE

The lightweight aggregate used in this work was expanded clay having a bulk density equal to 460 kg/m^3. The particle sizes of their grains range from 6 to 15 mm. This aggregate presented water absorption of 15%, 20%, 25%, and 30% at 15 min, 30 min, 60 min, and 24 h, respectively. A limestone coarse aggregate was used in the reference concrete. In this case, a particle size distribution compatible to that observed in the expanded clay was obtained. In both normal and lightweight concretes, the fine aggregate was washed natural quartz sand, presenting medium-fine particle size distribution; the cement used was a Portland cement CPV (high initial strength) that corresponds to the American Standard ASTM C150 (CP III), for not containing mineral admixtures, as blast furnace slags or pozzolans.

Chemical analysis of the lightweight aggregate was done to indentify the main elements. In the mineralogical characterization of the expanded clay and concretes, the main present crystalline phases were determined using X-ray difraction technique. A model PW-3710 (CuKα radition, current of 30 mA and voltage of 40kV, scan rate 0,060º/seg) PHILIPS difratometer was used.

5.2.1 Thermal analysis test

Powdered samples of the lightweight aggregate concrete (LWAC) and of the normal-weight concrete (NWC) were analyzed by thermogravimetry (TG) and differential thermal analyzes (DTA) originating the curves TG and DTA, that were obtained starting from temperatures that varied from 25 to 900 °C, in air dynamics atmosphere, to 10 °C/min, in aluminum melting pot. The analyses were accomplished in a NETZSCH thermal-analyzer, STA409EP model. These techniques allowed the evaluation of the behavior of the concrete when submitted to high temperatures.

5.2.2 Thermal expansion test

The determination of the thermal expansion coefficient of the concretes was accomplished following the procedures established by the NBR 12815 standard [8]. Two cylindrical specimens of 15 cm of diameter and 30 cm of height were molded, for the NWC and for the LWAC, with estimated compressive strength of 40 MPa. For the deformation measurement, KYOWA Strain Gage electric model KC-70-120-A1-11 were used, fixed in the cylinders external surface. The specimens were, then, stabilized in the temperature of (23 ± 2)°C, and later, put in a heated camera with temperature of (38 ± 2)°C, where they remained for 48 hours. Soon afterwards, they were transferred to a cooled camera with temperature of (4 ± 2)°C for 48 hours. The heating and cooling cycles were repeated until a resulting thermal expansion dispersion of 10% maximum. The coefficient of thermal expansion on the 28th day was determined by Equation 1.

$$\alpha = \frac{\varepsilon q - \varepsilon f}{Tq - Tf} \qquad \text{(Equation 1)}$$

were:

α - Thermal expansion coefficient (x 10^{-6}/ °C);

εq – Specific strain, calculated starting from the reading of stabilized origin (x 10^{-6});

εf – Specific strain, calculated starting from the readings of the strain gage (x 10^{-6});

Tq - Internal temperature of the specimen in origin room (°C);

Tf - Internal temperature of the specimen in test room (°C).

To complement the results obtained in the previous analyzes, the thermal expansion of the concretes was evaluated using a dilatometer. Prismatic concrete specimens were molded with reduced dimensions of 1 x 1 x 2 cm, composed by small aggregates of limestone and of expanded clay with approximate diameters of 5 mm as it can be seen in Figure 5.2. These specimens were submitted to heating cycles from 25 to 900 °C and cooling from 900 to 25 °C. The relative expansion at these temperatures was determined using a LVDT (Lineal Variable Differential Transformer) sensor.

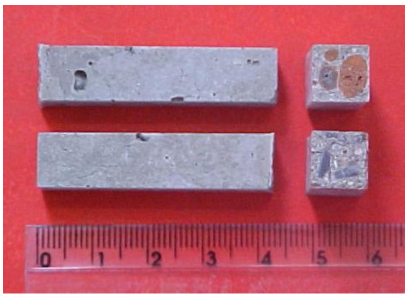


Figure 5. 2 – Specimens of the LWAC and NWC for analysis in dilatometer

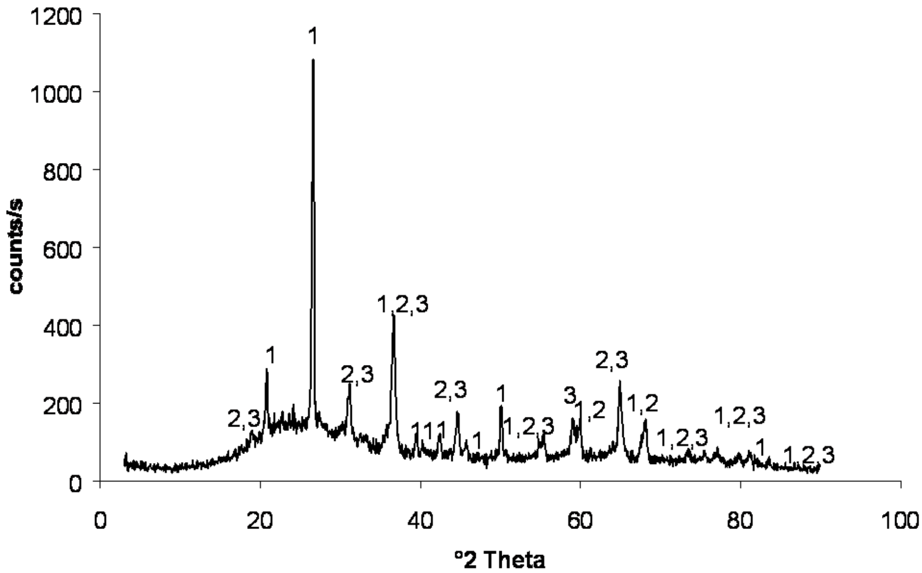
5.3 RESULTS AND DISCUSSION

5.3.1 X ray diffraction (XRD)

Table V.1 presents the chemical analysis of the expanded clay. Figure 5. 3 show the spectrum of the expanded clay with its main elements obtained by X-ray diffraction.

Table V. 1 - Chemical analysis of expanded clay.

Chemical analysis										
Oxide	SiO_2	Fe_2O_3	Al_2O_3	K_2O	MgO	TiO_2	Na_2O	CaO	S	LOI
(%)	63.4	11.7	10.5	4.3	3.7	0.42	0.39	0.25	0.02	0.81



1- SiO_2 - Silicon (α-Quartz);
2- $Mg(SiO_4)$ - Magnesium Silicate;
3- $MgAl_2O_4$ - Magnesium Aluminum Oxide (Spinel).

Figure 5. 3 – Spectrum of the expanded clay obtained by X-ray diffraction.

It was observed in the diffratogram showed in Figure 5.3 the presence of magnesium aluminum oxide (Spinel) formed at 980 °C during the pyroplastic expansion of the expanded clay. The Spinel reacts with the chemical elements (Na, K, Ca, Mg and Fe), during the production process of the expanded clay, forming a glass phase (peel of the aggregate). In the analysis by X-ray diffraction, the main elements found in the NWC were the dioxide silicon (SiO_2), calcium hydroxide ($Ca(OH)_2$), calcite ($CaCO_3$), hydrated calcium silicate (Ca SiO_4 0,3H_2O), whereas in the LWAC the main elements found were the dioxide silicon (SiO_2), calcium hydroxide ($Ca(OH)_2$), magnesium aluminum oxide (Mg Al_2O_4), and the hydrated calcium silicate (Ca SiO_4 0,3H_2O).

5.3.2 Thermal analysis

Figures 5.4 and 5.5 present the thermal analyses obtained by the termogravimetry curves (TG), differential termogravimetry (DTG) and differential thermal analysis (DTA) for the concretes with an estimated compressive strength of 40 MPa.

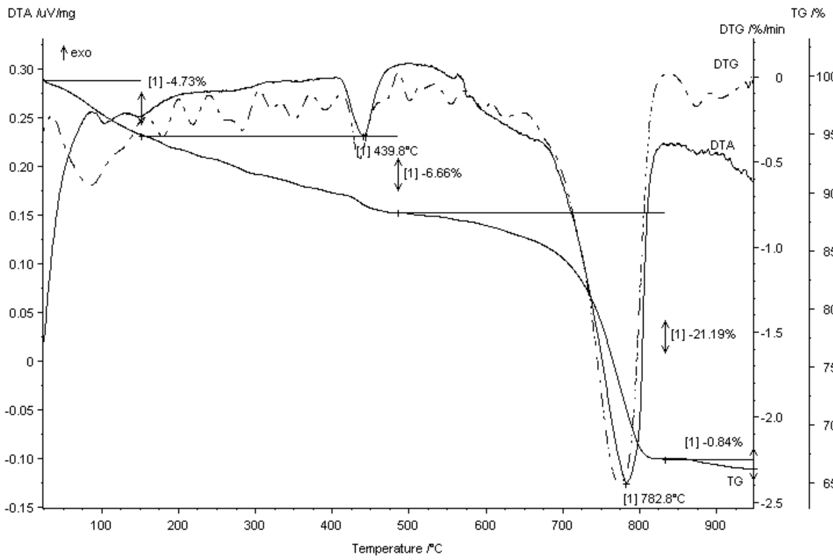


Figure 5. 4 – Termogram of the NWC.

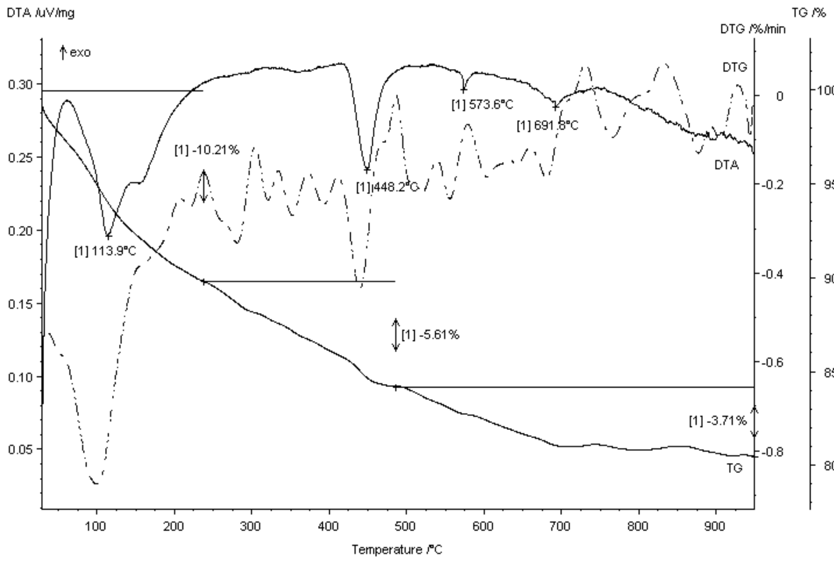


Figure 5. 5 – Termogram of the LWAC.

In the Figures 5.4 and 5.5, it can be seen that the DTG and DTA curves presented endothermic peaks, characteristic of the decomposition of present phases in the concretes. Tables V.2 and V.3, summarize the results of the thermal analyzes for the two concrete types. The weight loss and the temperature intervals were obtained by TG curves, whereas the peak temperatures were identified in the DTA curves.

Table V. 2 – Thermo analysis of the NWC.

Phases analized	Temperature intervals (°C)	Peaks of the reactions (°C)	weight loss (%)
H_2O	25 – 150	103	4,72
$Ca(OH)_2$	150 – 485	440	6,66
α-Quartzo/β-Quartzo	525 – 570	562	-
$CaCO_3$	690 – 829	783	21,19
Others losses	829 – 950	-	0,84
Total	-	-	33,41

Table V. 3 – Thermo analysis of the LWAC.

Phases analized	Temperature intervals (°C)	Peaks of the reactions (°C)	weight loss (%)
H_2O	25 – 237	114	10,21
$Ca(OH)_2$	237 – 488	448	5,60
α-Quartzo/β-Quartzo	537 – 580	574	-
$CaCO_3$	654- 725	692	3,11
Others losses	725 – 950	-	0,6
Total	-	-	19,52

It can be observed, from the results presented in the Tables V.2 and V.3, that a smaller loss of total mass of the LWAC is verified when compared to the NWC, characterizing larger thermal stability of the concrete with expanded clay aggregate in relation to the concrete with limestone, when submitted to change of temperature from 25 to 950 °C. Therefore, for the same estimated compressive strength, the LWAC presented larger thermal resistance in relation to the NWC.

The LWAC presented larger loss of water when compared to the NWC, due to evaporation of the moisturizing water inside the expanded clay aggregate. In the NWC the weight loss regarding the dehydroxilization of $Ca(OH)_2$ and decomposition of $CaCO_3$ was more larger than to the LWAC due the limestone used as coarse aggregate in the first one. The presence of quartz is related largely to the fine aggregate, present in both concretes. The other losses can be related to the dehydroxilization of the C-S-H present in the cement paste. The results of the thermal analyses of some phases of the analyzed concretes are similar to the obtained by other researchers [9, 10, 11].

5.3.3 Thermal expansion

Figure 5.6 presents the linear expansion curves of the LWAC and NWC for heating cycles (25 to 900 °C) and cooling cycles (900 to 25 °C), obtained by dilatometer.

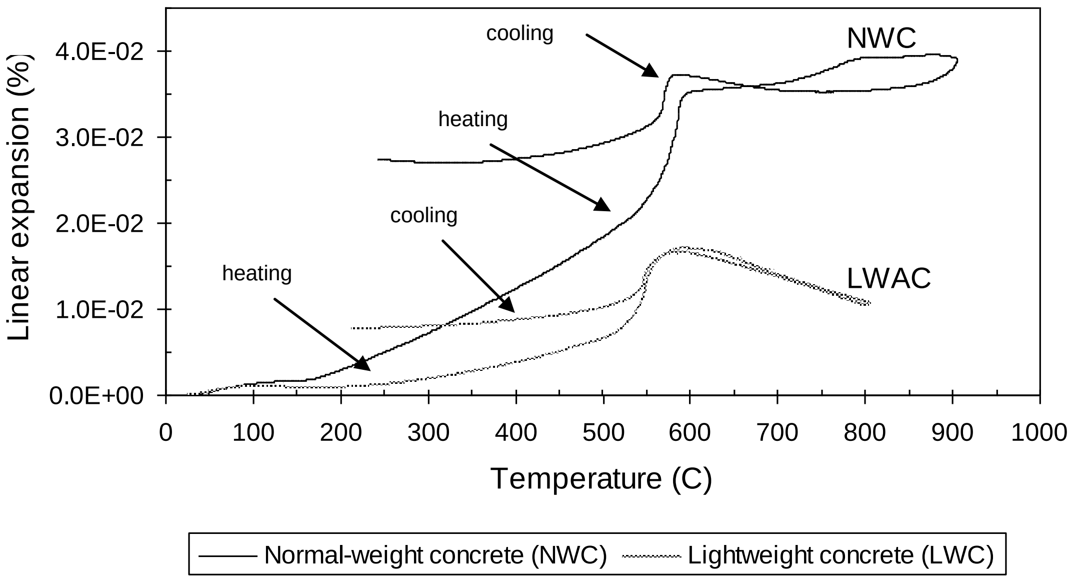


Figure 5. 6 – Linear expansion of the concretes in function of the temperature

It can be verified, from the inclinations of the curves of Figure 5.6 that the coefficients of linear expansion of the concretes varied according to the temperature, being this variation smaller, for the LWAC when compared to the NWC. Between 100 and 200 °C stabilization of the expansion takes place, due to a small contraction associated to the loss of water, annulling the effect of dilation of the aggregates. The maximum values of thermal expansion were close to 1,5% (3×10^{-3} mm) for the LWAC and 3.5% (7×10^{-3} mm) for the reference concrete, obtained around 600 °C. The largest expansion that took place around this temperature can be explained by the change of the morphology of the α-quartzo to β-quartzo, resulting in an increase of molecular volume. Above 650 °C contractions in both concretes take place, in larger proportion in the LWAC, which can be associated to the dehydroxilization of the C-S-H.

Overall LWAC presented smaller thermal expansion in relation to the NWC indicating a larger thermal resistance and a larger durability of this concrete type when submitted to high temperatures. This behavior is influenced by the low thermal conductivity of the LWAC (1.131 W/m K) when compared to the NWC (2.538 W/m K), which delays the heat flow in its interior, protecting itself and the steel reinforcement (Chapter 4).

The curves obtained during the cooling cycles followed the opposite direction of the heating curves and, in general, they presented similar thermal expansion values to the obtained on the first cycle above 550 °C. This behavior shows that there was not thermal degradation of the samples after they were submitted to temperatures up to 900 °C. In the cooling phases with temperatures below 550 °C, the obtained values were bigger than those of the heating cycle, which represents a residual deformation of the analyzed materials that do not presents perfectly elastic behavior.

Table V.4 presents the results obtained for the coefficients of thermal expansion of the analyzed concretes.

Table V. 4 – Thermal expansion coefficients of the concretes.

Concretes	Specimens	Thermal expansion coefficient ($x\ 10^{-6}$ °C^{-1})	Average coefficient ($x\ 10^{-6}$ °C^{-1})
NWC	1	14.64	15.50
	2	16.35	
LWAC	3	12.75	11.94
	4	11.12	

The values obtained for the coefficients of thermal expansion of the two concrete types did not greatly differ for temperature variations between 4 and 38 °C. However there was smaller thermal expansion in the LWAC. This behavior confirms the smallest thermal expansion coefficient of the LWAC in relation of the NWC obtained in the previous analyzes.

The measured values for the coefficient of thermal expansion of the LWAC are within the limits suggested by Neville [7] for cement mortars (8 and 12 x 10^{-6} °C^{-1}). As the thermal expansion coefficient of the expanded clay influences in the expansion coefficient of the LWAC, and as this coefficient came closer to the coefficients of mortars; smaller thermal stress should occur inside of this concrete, contributing, in that way, for a smaller micro-cracking in LWAC when compared with NWC.

5.4 CONCLUSIONS

The formation of chemical compositions such as the spinel and of a glass phase during the thermal treatment (pyroexpansion), in the process of production of the expanded clay, contributes to a greater thermal resistance of that aggregate.

The X-ray diffraction of the NWC evidenced the presence of silicon (SiO_2) in the morphology of the α-quartzo which is transformed to β-quartzo at temperatures around 600 °C, presenting a considerable volumetric expansion.

For the same mixture proportion, the LWAC presented smaller weight loss in the thermogravimetry analyzes, due to the smallest losses related to the dehydroxilization of $Ca(OH)_2$ and the decomposition of $CaCO_3$ obtained for that concrete type. The smaller weight loss and consequently larger thermal stability of the LWAC may be correlated to a larger thermal resistance of that concrete in relation to the NWC.

The larger proximity between the coefficient of thermal expansion of the LWAC and the coefficients of expansion of the mortars, in relation to the coefficients of the NWC, will probably contribute to a smaller micro-cracks incidence and a consequent increase in the durability of the LWAC.

The LWAC presented smaller thermal expansion and smaller residual deformation in relation to the NWC, during heating cycles up to 900 °C. This behavior is due to a smaller thermal conductivity of the LWAC and it is proof of the greater thermal resistance and greater durability of that concrete type, even when submitted to high temperatures.

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CAPÍTULO 6 - Influence of the Expanded Clay Aggregates in Abrasion Resistance of Structural Lightweight Concrete

Note: Submitted to the V International Congress ACI/CANMET, 2008, Manaus.

Authors: Weber Guadagnin Moravia, Conrado de Souza Rodrigues,
Adriana Guerra Gumieri, Wander Luiz Vasconcelos.

Abstract

Durability is one of the key factors considered in the specification of concrete for most of its applications. When applied to industrial floors, road pavements and sidewalks, abrasion wearing reduces the concrete performance. This work is focused on the abrasion resistance of lightweight concrete produced with expanded clay, comparing it to the performance of a conventional concrete produced with normal-weight aggregates, with the same mixture proportion. The lightweight aggregates structure was investigated through mercury intrusion porosimetry and water absorption tests. The parameters used to evaluate the abrasion phenomena were thickness and mass loss of the concretes, which were resulted from the friction between the specimens and an abrasive material. Although the expanded clay presents lower abrasion resistance than the normal-weight aggregate, due to its higher porosity, both concretes behaved similarly regarding their wearing resistance. The denser interfacial transition zone between the expanded clay and the cement paste in the lightweight concrete seems to have compensate the lower wear resistance of the aggregate.

Keywords: abrasion resistance; lightweight concrete; transition zone.

6.1 INTRODUCTION

Surface wearing is one of the factors related to the decreasing durability of concrete floors and pavements. The deterioration through surface wearing can be caused by abrasion, erosion or cavitation, leading to the progressive loss of concrete mass. The term abrasion refers to the dry attrition in floors and pavements, while the term erosion is concerned to the wearing caused by the contact of the concrete surfaces with fluids. Cavitation is related to the formation and rupture of gas bubbles in pipes.

The most important mechanism of surface wearing in concrete is the abrasion, through which the material loss in industrial floors and in road and sidewalks pavements occur as it can be seen in Figure 6.1. It is not associated with the loss of mechanical performance of the concrete structure, but with its functionality.

Figure 6. 1 – Abrasion wearing on the surface of a concrete industrial floor.

Factors affecting the wearing resistance of concrete to abrasive action include aggregate hardness, mixture proportions, casting control, curing and the interface between the cement paste and the aggregates [1]. Abrasion affects mainly the cement paste, which presents low attrition resistance. Therefore, the coarse aggregate, due to its hardness, represents the most important phase of the concrete to its surface wearing resistance [2]. Besides, the bonding between the coarse aggregates and the cement paste determines the intensity of the disaggregation in concretes [3,4].

Adequate mixture proportions contribute to a proper w/c and paste porosity, which are responsible for the achievement of a compact cement paste, resulting in a concrete with higher compressive strength. In general, compressive strength of concretes and its wearing resistance are directly proportional [5].

Casting control avoids bleeding and segregation of the materials, which promotes the concentration of coarse aggregates in the bottom of the concrete components and its upper surface composed mostly by mortar, reducing the wearing resistance of the component. Proper curing and effective bonding between the cement paste and the coarse aggregate result in a better, more cohesive, microstructure and avoid the micro-cracking due to shrinkage and thermal expansion. The interface between the coarse aggregate and the cement matrix is usually the weakest part of the microstructural system of the concrete, the place where the cracks start. This can influence the concrete disaggregation [6].

Due to its porous surface, the expanded clay can promote stronger adherence between the aggregate and the cementitious matrix. The water absorbed by the aggregates during the concrete mixing procedure becomes available for the cement hydration, and a great part of the additional hydration happens in the interface between the aggregates and the matrix [7]. This study is then focused on how this better developed interfacial transition zone influences the abrasion of lightweight aggregate concrete (LWAC), comparing it with a normal-weight concrete (NWC).

6.2 EXPERIMENTAL PROCEDURE

The production and characterization of the expanded clay used as the lightweight aggregate in structural concrete were described in [8]. A limestone coarse aggregate was used in the reference concrete. In this case, a particle size distribution compatible to that observed in the expanded clay was obtained. In both NWC and LWAC the fine aggregate was washed natural quartz sand, presenting medium-fine particle size distribution. This size distribution was chosen as it avoids segregation of the expanded clay in the lightweight concrete.

The water absorption of the expanded clay, and its evolution at different time intervals, was evaluated following the method described in [9]. The apparent porosity of the expanded clay and limestone aggregates were established using mercury intrusion porosimetry. Aggregates with dimension of 9,5 mm were chosen, as it represents the major part of the coarse aggregate distribution studied.

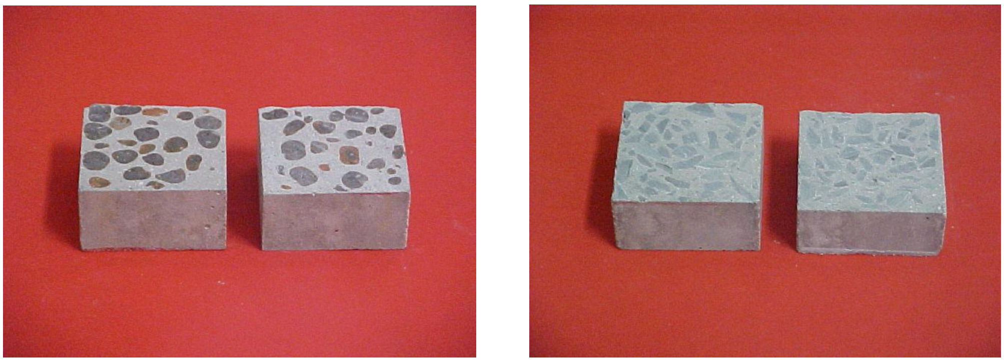
For the compressive strength tests, 4 different mixture proportions were adopted for the NWC, with estimated compressive strength of 20 MPa, 25 MPa, 30 MPa and 40 MPa. The same proportions established were applied in the LWAC production. For each mixture proportions, ten cylindrical specimens were molded (diameter of 10 cm and height of 20 cm), following Brazilian standards [10]. The specimens were moist cured and tested at the ages of 3, 7 and 28 days, in agreement with [11]. The results were applied in the evaluation of the relationship between the compressive strength and the abrasion resistance for concretes.

6.2.1 Abrasion test

For the concretes with an estimated compressive strength of 40 MPa, the abrasion resistance was evaluated through a test adapted from [12], which is similar to that described in ASTM C 779-76 [13]. In this test, the surface of a fixed concrete sample is put in contact with a cast iron disc which rotates at 30 rpm. Between the disc and the sample, standardized sand, classified by Brazilian standard as number 50 (ϕ=0,3 mm), was used as the abrasive material [14]. The abrasion is evaluated in terms of mass and thickness loss after a number of rotations corresponding to 500 m and 1000 m. The equipment used in this test is shown in Figure 6.2.

Figure 6. 2 – Surface wearing machine for abrasion resistance of concrete.

Two specimens of each type of concrete were subjected to the abrasion tests at 28 days of age. These were taken from molded cylindrical specimens of 10 cm x 20 cm, which were sawed in order to obtain a 7 cm x 7 cm transversal area, as shown in Figure 6.3. The thickness of these samples was approximately 3 cm.



(a) lightweight concrete (b) normal-weight concrete

Figure 6. 3 – Specimens of concretes for the abrasion test.

The direct parameter obtained from the abrasion test was the mass loss of the samples. Considering the density of the LWAC and NWC, this mass loss can be used to estimate the decrease in the samples volume. As the transversal area remains constant after the test, the decrease in the volume can be applied to calculate the thickness loss.

6.2.2 Scanning electron microscopy (SEM) analysis

The morphology of the expanded clay and transition zone between the coarse aggregates and the cement matrix were evaluated through the microstructrural analysis, using scanning electron microscopy (SEM). A microscope JSM-80 PHILIPS was used, being the samples covered with carbon film to be conductive. The images were obtained by secondary electrons.

6.3 RESULT AND DISCUSSION

6.3.1 Water absorption

In agreement with the results presented in Table VI.1, it is verified that the expanded clay presents high absorption of water in relation to the limestone aggregate, which is related to the porous structure of their grains. It was verified that, after 24 hours, the water absorption was not stabilized, as suggested in [15]. In spite of that, it was not necessary to continue with the saturation test, as a major part of the absorption was obtained within 60 minutes of immersion.

Table VI. 1 - Results of the water absorption of the expanded clay.

Period	5 min	15 min	30 min	60 min	24 h
Water Absorption (%)	15	15	20	25	30

6.3.2 Mercury intrusion porosimetry (MIP) - aggregates

In Table VI.2, the results of the mercury intrusion porosimetry tests are presented for the limeston and lightweight aggregate. It is shown that the expanded clay presents higher apparent porosity, corroborating with the aggregate's high absorption.

Table VI. 2 - Results of the mercury intrusion porosimetry for the conventional and lightweight aggregates

Samples	Total Pores Area (m^2/g)	Average Pores Diameter (μm)	Apparent Porosity (%)
Limestone	0.01	1.31	1.00
Expanded clay	3.12	0.22	18.54

6.3.3 Density of the concretes

In Table VI.3, the density of NWC and LWAC, for mixture proportions of 40 MPa at ages of 3, 7 and 28 days, are shown. These values were used in the calculation of thickness loss during the abrasion tests.

Table VI. 3 - Density of the concrete analyzed.

Density of the concrete (kg/m^3)				
Estimated Compressive Strength	Concrete	Age (days)		
		3	7	28
(40 Mpa)	NWC	2346,1	2367,3	2409,8
	LWAC	1613,6	1643,5	1645,4

The results of the compressive axial strength of the concretes, for the ages of 3, 7 and 28 days, are presented in Table VI.4 and Figure 6.4. Considering the direct relation between compressive strength and abrasion resistance of concretes as reported in the literature [5], NWC should present higher wearing resistance due to the lower compressive strength of the LWAC when compared with the first one.

Table VI. 4 - Compressive strength of the concretes.

Estimated Compressive Strength (MPa)	Concrete	Compressive strength (MPa)								
		3 days	Mean	S_d	7 days	Mean	S_d	28 days	Mean	S_d
40	NWC	32.8	33.4	2.9	35.9	35.1	1.1	46.5	46.6	3.5
		30.8			34.3			43.2		
		36.5			44.6*			50.2		
	LWAC	28.4	27.5	0.7	28.6	29.2	0.7	30.2	33.4	3.1
		27.3			28.9			36.2		
		26.9			30.0			34.0		

* Values not taken into account. S_d – Standard deviation

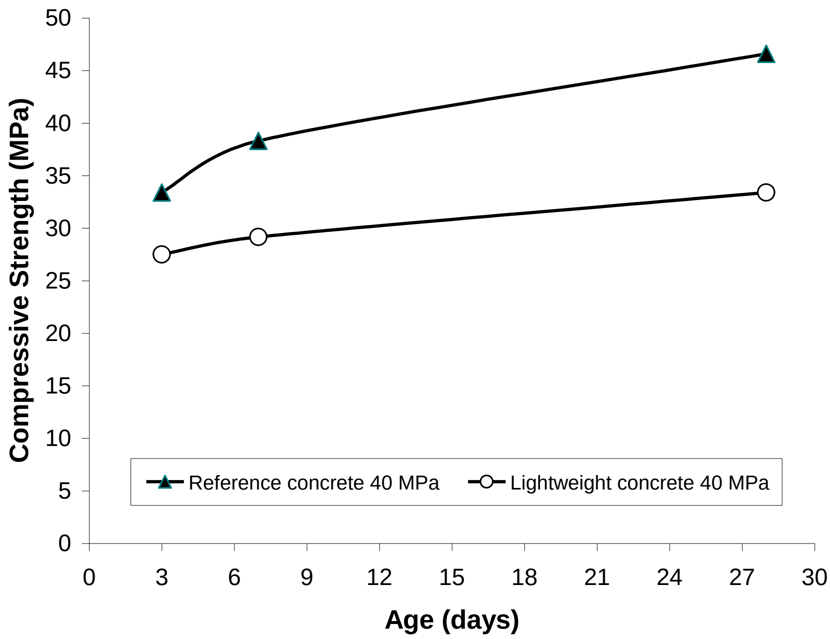


Figure 6. 4 - Evolution of the compressive strength of concretes.

6.3.4 Abrasion resistance

The weight loss after the abrasion test, correspondent to 500 m and 1000 m of friction of the concrete against the abrasive material, is shown in Table VI.5. After a wearing correspondent to 1000 m of friction with the abrasive material, the LWAC presented a weight loss 1,2% lower than that of the NWC.

Table VI. 5 - Weight loss of the concrete samples after the abrasion tests.

Concrete	NWC		LWAC	
Samples	1	2	1	2
Initial weight (g)	340.0	389.2	271.2	301.7
Weight after a correspondent 500m of wearing (g)	331.6	374.3	260.5	296.0
Weight loss after 500m of wearing (%)	2.5	3.8	3.9	1.9
Average weight loss after 500m of wearing (%)	3.1		2.9	
Weight after a correspondent 1000m of wearing (g)	321.2	370.3	259.0	291.4
Weight loss after 1000m of wearing (%)	5.5	4.9	4.5	3.4
Average weight loss after 1000m of wearing (%)	5.2		4.0	

The thickness loss after a wearing corresponding to 1000 m of friction between the concrete samples and the abrasion material, calculated from the weight loss results, is shown in Table VI.6. Although, for an estimated compressive strength of 40 MPa at 28 days the LWAC has presented a strength around 28% lower in relation to the NWC, the results of mass and thickness loss to the LWAC presenting slightly higher wearing resistance, does not correspond to what would be expected. Therefore, the direct relation between compressive strength and wearing resistance was not observed in the concretes investigated.

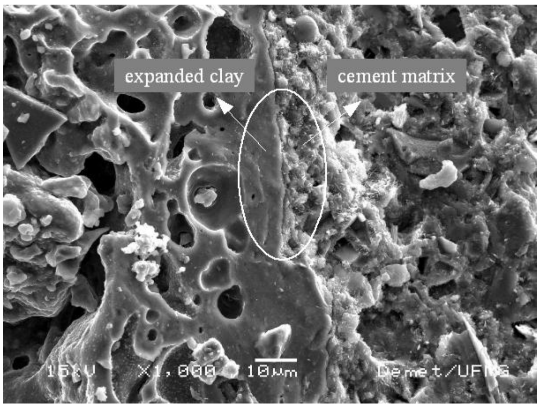
Table VI. 6– Average initial and final thickness and average thickness loss.

Concrete	Average initial thickness (mm)	Average final thickness (mm)	Average thickness loss (mm)
NWC	30.9	29.3	1.6
LWAC	35.5	34.1	1.4

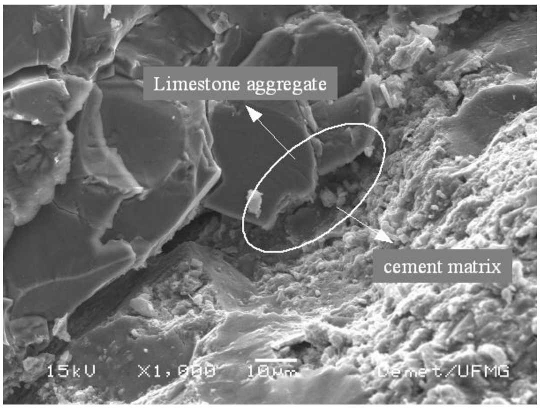
6.3.5 Scanning electron microscopy (SEM)

The Figure 6.5 presents the SEM images to avaliated. It can be observed a better adherence in the interface between the expanded clay and the matrix in the lightweight concrete (Figure 6.5a, 6.5c), comparing to the interfaces in reference concrete (Figure

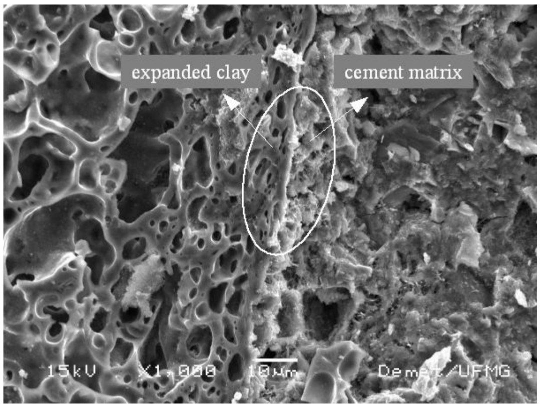
6.5b, 6.5d). In Figure 6.5d, a micro-crack can be observed in the interfacial transition zone.



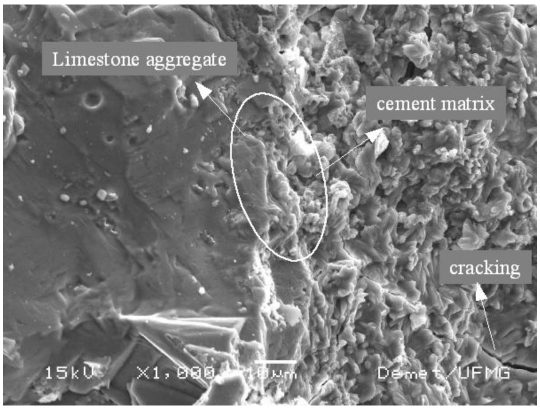
(a) Lightweight concrete – 40 MPa



(b) Reference concrete – 40 MPa



(c) Lightweight concrete – 40 MPa



(d) Reference concrete – 40 MPa

Figure 6. 5 – Image analysis (1000X) obtained by scanning electron microscopy.

In Fig. 6.6, the image obtained at a magnification of 2000X shows the cement paste penetration in a surface pore of the expanded clay. This is observed in porous aggregates or aggregates with a wrinkled surface and promotes a better interfacial bond characterized by mechanical interlocking.

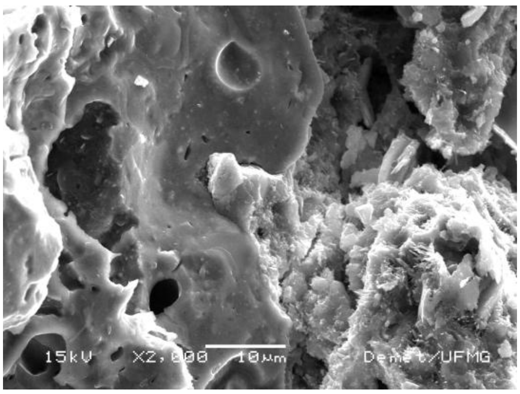


Figure 6. 6 - Mechanical interlocking between the cement matrix and the expanded clay

The better developed interfacial transition zone observed in the LWAC could be the responsible for the higher abrasion resistance of this material, compensating the lower hardness of the lightweight aggregate.

6.4 CONCLUSIONS

Comparing to the limestone aggregate, the expanded clay presents lower density, and higher porosity due to the porous structure of its particles. This contributes to the penetration of the cement matrix on the pores of the aggregate.

For an estimated compressive strength of 40 MPa at 28 days, the LWAC presented a slightly higher abrasion resistance than the NWC for a wearing correspondent to 1000 m of friction between the concrete and the abrasive material.

The coarse aggregate - cement matrix interface is better developed, more compact and free of micro-cracking, in the lightweight concretes. This is due to the mechanical interlocking between the cement paste and the porous surface of the expanded clay, as evidenced in the SEM studies.

The mechanical interlocking can improve the bond between the expanded clay and the cement matrix in the transition zone, resulting in increased abrasion resistance of the lightweight concrete.

The better adherence observed in the interface of the lightweight concrete compensates the lower hardness of the expanded clay, leading to an abrasion resistance which was beyond of what was expected, considering the relation between compressive strength and abrasion resistance reported in the literature.

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CAPÍTULO 7 - Evaluation of the Durability of the Structural Lightweight Aggregate Concrete by Water Permeability and Water Absorption

Note: To be submitted to the journal Cement and Concrete Composites
Authors: Weber Guadagnin Moravia, Wander Luiz Vasconcelos.

Abstract

Most of the deterioration processes in concrete involve permeation of fluids through its pore systems compromising its durability. This paper presents an experimental study to evaluate indirectly the durability of concretes. The durability of structural lightweight aggregate concrete (LWAC) was evaluated in comparison to normal-weight concrete (NWC) using parameters with porosity, absorption and permeability. These properties were investigated through water absorption, capillary absorption, permeability, and mercury intrusion porosimetry tests. Specimens of both concretes were cast with the same mix proportions. The only difference between them was the coarse aggregate used. Assays were also done in expanded clay and limestone aggregate. The results indicated a greater resistance to the action of harmful fluids and consequently a greater durability as to LWAC in relation to NWC.

Keywords: lightweight concrete; porosity; water permeability; water absorption.

7.1 INTRODUCTION

The number of concrete structures with some kind of deterioration has increased considerably in the last decades, due to the exposure of those structures to an urban atmosphere, with concentrations of aggressive substances continuously increasing. As a consequence, the mechanical strength should not be the only factor to be considered in the specifications of concrete structures and the analysis of other acting criteria, as the durability, has become more and more significant.

Most of the processes of concrete deterioration are related to the penetration of fluids through the capillary pores, present in the mortar and in the aggregates of the concrete. Among the main substances that can reduce the resistance and commit the durability of the reinforced concrete structures, pure water or with dissolved ions can be mentioned, especially the chlorine ions and the sulfates ions, the carbon dioxide (CO_2), and the oxygen.

The intensity of degradation of the concrete structures will depend on the characteristics of its pores structure, of the mechanisms and taxes of penetration of fluids, and of the concentrations and presence substances in these fluids. The mechanisms related to the transport of fluids or dissolved ions to the interior of the concrete can happen as: permeability, diffusion, capillary absorption and migration. Permeability is the measure of the flow of a fluid due to pressure differences; diffusion is the process that balances concentration gradients; capillary absorption, subsequently, is due to the capillary forces; while the migration is the flow of ions, when there is a difference of eletrical potential [1].

The capillary absorption is one of the main mechanisms of transport of liquids, provoked by capillary forces caused by the superficial tension of the liquid in their interior. This absorption increases with the increase of the water/cement ratio and for each w/c ratio, the absorption increases as the paste content in the mix. The capillary absorption is also very much influenced by the moisture content of the concrete and by cure condition which can avoid internal micro-cracking [2].

The permeability of a material is influenced by its porosity, applied pressure and viscosity of the fluid that will penetrate its net of pores [3]. The durability of the concrete structures is directly related to the permeability of fluids, which usually find a preferential way in the transition zone between the mortar and the coarse aggregate [4]. Micro-structural factors as porosity, distribution of sizes of pores, and values of permeability of the concrete can be used as qualitative indicators of its durability [5,6,7]. These factors may be related to the permeability of harmful fluids, diffusion of composites as the carbon dioxide, and migration of sulfates and chlorine ions inside the concrete, leading to its deterioration.

7.2 EXPERIMENTAL PROCEDURE

In this work, the expanded clay was used the aggregate in LWAC. Specimens of NWC and LWAC were cast with the same mix proportions established, for an estimated compressive strength of 40 MPa. It was adopted in this research a methodology to determine the absorption of water, the permeability, and parameters of the pore structure as porosity and pore-size distribution, for LWAC and NWC.

7.2.1. Water absorption by immersion test

For evaluation of the water absorption by immersion, it was used as reference NBR 12766 [8], that establish the test criteria for the determination of the absorption in rocks. Prismatic specimes were molded for both concretes with dimensions of 7 x 7 x 28 cm, later sawed from 3 to 3 cm at 28 days of age. As for LWAC and the NWC, 10 samples of 7 x 7 x 3 cm of different specimes were selected, excluding the samples of the extremities. The samples were dried in a stove up to 100 °C, weighed and put in a container where water was added, corresponding approximately to 1/3, 2/3 and 3/3 of the height of the sample (3 cm), at every 4 h period. After 24 h of the last addition of water, the samples were weighed in the condition saturated dry surface condition and in the submerged condition for the determination of the porosity and absorption of apparent water using Equation 7.1c e d.

(a) dry specific gravity: $\rho_{sec} = m_1 / (m_2 - m_3)$ (kg/m³);

(b) saturated specific gravity: $\rho_{sat} = m_2 / (m_2 - m_3)$ (kg/m³);

(c) apparent porosity: $\eta = [(m_2 - m_1) / (m_2 - m_3)] \times 100$;

(d) apparent water absorption: $\alpha = [(m_2 - m_1) / m_1] \times 100$ (Equations 7.1)

Were:

m_1 - mass of the sample dried in greenhouse (g);
m_2 - mass of the sample in the saturated dry surface condition (g);
m_3 - mass of the sample in the submerged condition (g);
ρ_{sec} – dry specific gravity (kg/m³);
ρ_{sat} – saturated specific gravity (kg/m³);
η - apparent porosity (%);
α - apparent water absorption (%).

7.2.2 Capillary absorption test

The capillary absorption of the concretes was determined, at 28 days of age, in agreement with an adaptation of the methodology proposed by the LNEC E 393 [9]. Figure 7.1 illustrates the prismatic specimens of LWAC and of NWC, molded with dimensions of 7 x 7 cm of base and 28 cm of height, put in a container with a sheet of water of 10 mm. Weightings were made before the immersion, and at 2, 24, 48 and 168 hours of immersion.

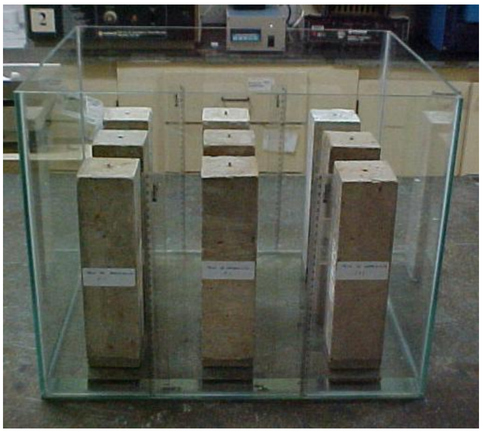


Figure 7.1 - Prismatic specimens in contact with the sheet of water of 10 mm.

The capillarity coefficient was determined in agreement with Equation 7.2.

$$C_t = \frac{m_t - m_i}{S\sqrt{t}} \qquad \text{(Equation 7.2)}$$

Where:

C_t = capillarity coefficient after the time "t" of immersion ($kg/m^2 \cdot h^{0,5}$);

m_2 = mass of the specimen in the previous interval (kg);

m_t = mass of the specimen after the time "t" of immersion (kg);

S = area of the specimen in contact with the water (m^2);

t = time of immersion (h).

7.2.3 Water permeability test

The test was conducted in accordance with NBR 12689 [10]. This test measures the permeability applying the pressure of 2.1 MPa forcing the passage of the water through the specimen and measuring the speed of percolation of the liquid. Two cylindrical specimens were cast with 15 cm of diameter and 30 cm of height for LWAC and for NWC. The tops of the specimens were sawed at 7,5 cm of the plane faces, establishing a relationship height/diameter equal to 1 (one), in order to minimize the exudation and carbonation effects.

The Figure 7.2 displays the preparation of the specimens for the permeability test of the concretes at 28 days of age. The lateral face of the specimens was wear using jets of sand, and painted with an asphalt mixture Figure 7.2a, and the space between the specimen and the campanula of steel was filled out with the same mixture (Figure 7.2b), with the aim of assuring that the flow of water went vertically through the interior of the concrete.

(a) (b)

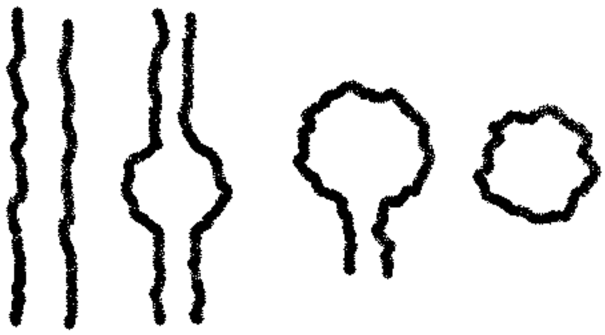
Figure 7. 2 – Preparation of the specimens for permeability test of the concretes.

Source: FURNAS (1997).

7.2.4 Mercury Intrusion Porosimetry (MIP) test

MIP was adopted for the study of porosity and pore-size distribution of aggregates and concretes. This technique is suitable to evaluate pores with diameters varying from 0.01 to 100 μm forcing mercury into the vacated pores of a body by the application of pressure. Test was performed on a mercury porosimeter Auto-Pore III 9410 from Micromeritics, having a pressure range from sub-ambient to 415 MPa.

This method allows evaluate the capillary pore geometry by data interpretation classified as a continuous pore, a continuous pore with *inkbottle*, a dead-end pore with *inkbottle* or an isolated pore, as it can be observed in Figure 7.3. The isolated pore cannot be detected by MIP, because it does not contributes with mercury transport. The amount of inkbottle pores can be estimated from the hysteresis that can be seen in the graph of the cumulative intrusion volume against pore diameter [11].



(a) (b) (c) (d)

Figure 7. 3– Classification of capillary pore geometry: a) continuous pore, b) continuous pore with *inkbottle*, c) dead-end pore with *inkbottle*, d) isolated pore.
Source: Ye (2003).

Aggregates with dimension of 9.5 mm were chosen, as they represent the major part of the coarse aggregate distribution studied. Short cylindrical specimens for both concretes were molded with a diameter of 15 mm and height of 25 mm using aggregates with dimension of 5 mm, to avoid the influence of the exposed pores of the expanded clay in the results of the concrete porosity. It was opted for the determination of the volume of the samples and of the specimens, which eliminates the need of rigorous standardization of their dimensions and, yet, allows presenting the results in percentage terms. This procedure increases larger reliability in the analyses, because it eliminates part of the mistakes caused in the choice of the samples in the preparation of the specimens [12, 13].

7.3. RESULTS AND DISCUSSION

7.3.1 Mercury intrusion porosimetry (MIP)

In Table VII.1 the results of the MIP tests are presented for the limestone and expanded clay aggregate, NWC and LWAC on the 28th day.

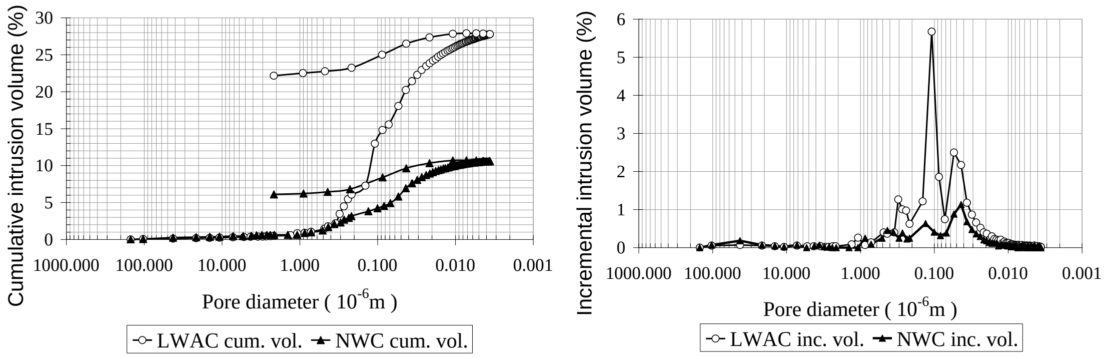
Table VII. 1 - Results of the MIP for the aggregates and concretes.

Samples	Total Pores Area (m^2/g)	Average Pores Diameter (μm)	Apparent Porosity (%)
Limestone	0.010	1.3100	1.00
Expanded clay	3.116	0.2200	18.54
NWC	5.101	0.0368	10.60
LWAC	16.843	0.0380	27.79

It can be verified that the expanded clay, in spite of having smaller average diameter of pores in relation to the limestone aggregates, it presents a larger total area of pores, corroborating with its largest porosity, and consequently, high absorption. That behavior contributes for a higher porosity presented for the LWAC when compared with the NWC, due the expanded clay utilized in the first concrete. The results obtained for the medium diameter of pores in LWAC approached, greatly, the results found for NWC, while the percentile differences among the porosities of the analyzed concretes were around 17%, corresponding to the difference observed among the porosities of the aggregates. This indicates that both concretes present a cement matrix with similar porosity and medium diameter of pores, as the same proportion for the molding of NWC and of LWAC was utilized.

7.3.2 Graphics of mercury intrusion porosimetry

The Figure 7.4 shows the graphics of mercury cumulative intrusion volume and mercury incremental intrusion volume obtained by MIP for both, NWC and LWAC. In Figure 7.4b the curves of incremental intrusion volume represent the volume of mercury intruded for each increment of diameter of the pores. It can be verified that in the zone of diameters of pores from 0.01 to 0.5 μm (capillary pores), a concentration of peaks with larger percentile of mercury intruded occurred, evidencing the largest incidence of pores in this area for both concretes. For NWC, besides the frequency of pores in this area, a larger incidence of pores with diameters between 10 and 100 μm was observed (macro-pores ϕ > 0.05 μm), and a more uniform distribution of the incremental volume peaks, in relation to LWAC. It can be verified for LWAC, that the largest peak of volume intruded corresponds to pores with diameters around 0.10 μm, that can be related, mainly, to the pores of the expanded clay, once in the analyses of MIP, that aggregate presented a medium diameter of pores around 0.22 μm (Table VII.1). It was observed that the sum of the percentile of the volume of mercury intruded in the pores with diameters between 0.01 and 1 μm represent about 2% and 9% of the total volume of the sample of NWC and of LWAC, respectively.



(a) Cumulative intrusion volume (b) incremental intrusion volume.

Figure 7. 4 –Mercury intrusion porosimetry test for NWC and LWAC.

The smallest pore dimension, in which an inflection in the curve of cumulative intrusion volume is established, is defined as critical diameter. The critical diameter characterizes a net of connected pores and it is frequently mentioned as durability parameter, because the connectivity of the pores influences the harmful agent's penetration. Therefore a smaller critic diameter means a greater difficulty for the harmful agents to penetrate the concrete [14]. It can be observed in Figure 7.4, that there was a slight difference, favorable to LWAC, in the critical diameter values, corresponding to 0.5 μm for NWC and 0.3 μm for LWAC.

The reason, between the minimum ordinate of the extrusion cycle and the maximum ordinate of the intrusion cycle, of the graph of cumulative intrusion volume versus pore diameter, indicates the estimated amount of *inkbottle* pores [11,13]. Taking the graph (Figure 7.4) into account, it was considered the amount of inkbottle pores, which was from 78% for LWAC and of 54% for NWC. Due to the form of those pores, a greater pressure is necessary so that they are filled out with the fluids. As LWAC presented a larger percentile of pores with that format, it can mean that, although that concrete has greater porosity, the geometry of their pores hinders the penetration of harmful fluids.

7.3.3 Water absorption by immersion

In Table VII.2 the values of the density (ρ) for the concrete samples in the dry and saturated conditions, apparent porosity (η) and water absorption (α) of NWC and of LWAC, are presented for the water immersion test.

Table VII. 2 – Results of density, porosity and water absorption of the NWC and LWAC.

Sample	ρ_{dry} (kg/m³)	ρ_{sat} (kg/m³)	η (%)	α (%)
NWC	2206	2353	14.70	6.67
LWAC	1561	1736	17.55	11.24

LWAC presented a reduction around 30% in the dry specific gravity in relation to NWC, staying inside the limits foreseen by other researchers [15, 16]. LWAC presented greater porosity than NWC, which can be attributed to the high porosity of the expanded clay, confirming the behavior previously observed in MIP (Table VII.1). Regarding of the water absorption, it can be verified that LWAC presented, approximately, double the absorption obtained for NWC, which can be explained, mainly, by the exposure of the expanded clay pores after the cut of the samples anticipated in this analysis.

7.3.3 Permeability and capillary absorption

Table VII.3 presents the capillarity coefficients for intervals among 2, 24, 48 and 168 hours, and the water permeability coefficient for NWC and LWAC.

Table VII. 3 – Capillarity and permeability coefficients of NWC and LWAC.

Specimens	Coefficient of capillarity ($kg/m^2 \cdot h^{0.5}$)				Coefficient of permeability ($\times 10^{-12}$ m/s)
	2 h	24 h	48 h	7th day	28th day
NWC	4.20	2.76	2.25	1.49	10.90
LWAC	3.00	2.39	2.02	1.27	0.85

LWAC presented inferior capillarity coefficients to the obtained for NWC in all of the intervals of time studied. It was observed that the capillarity coefficients decreased with time for both concretes, demonstrating that the capillary forces balanced themselves with the weight of the water column as time passes. LWAC also presented permeability coefficients to water inferior to those of NWC, validating the results obtained in both analyses. In spite of LWAC to have presented high porosity, its permeability coefficient to water was around 10 times smaller than the obtained for NWC. This can be explained by a smaller cracking index due to its best thermal performance (Chapter 4 and 5), and to probable improvements occurred in the transition zone between the expanded clay and the cement matrix. The behavior of LWAC indicates, as far as quality, greater resistance to the action of harmful fluids and consequently greater durability of that concrete in relation to NWC.

7.4 CONCLUSIONS

The expanded clay influenced in the high index of water absorption by immersion, due to its porosity and to the exposure of those pores in the preparation of samples of LWAC.

In spite of LWAC to have presented high porosity, its water capillarity absorption and water permeability coefficients were smaller than the obtained for NWC, which can be related to a smaller connectivity among the pores. This behavior indicates, as far as quality, smaller permeation of harmful fluids and consequently larger durability of LWAC in relation to NWC.

Micro-structural factors, as the diameter of pores and the geometry of pores of LWAC might have contributed for to smallest permeability of that concrete in relation to NWC. The smallest critical diameter and the largest percentile of pores in the form of "inkbottle", hinder the penetration of fluids in LWAC, promoting greater resistance of that concrete to the action of harmful fluids when compared to NWC.

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CAPÍTULO 8 - Evaluation of the CH Content and Densification Effect in the Transition Zone between Expanded Clay and Cement Matrix in Structural Lightweight Concrete

Note: To be submitted to the journal Cement and Concrete Research.

Authors: Weber Guadagnin Moravia, Adriana G. Gumieri Wander Luiz Vasconcelos.

Abstract

Recently the influence of the transition zone between the aggregate and the cement matrix in concrete has been studied however few researchers have worked on this subject concerning lightweight concrete. This work evaluates the microstructure of the transition zone between expanded clay aggregates and the cement matrix in structural lightweight concrete. Pozolanic activity, diffuse reflectance infrared Fourier transform spectrometry (DRIFTS), X-ray diffraction (XRD), scanning electron microscopy (SEM-EDS) methods were studied. From the results it was able to evaluate the influence of the expanded clay in the formation of the transition zone with the cement matrix. A transition zone denser and with better mechanics interconnections was observed between expanded clay and cement matrix in lightweight aggregate concrete (LWAC) than the existing between the limestone aggregate and cement matrix in normal-weight concrete (NWC).

Keywords: lightweight concrete; microstructure; transition zone.

8.1 INTRODUCTION

Nowadays, more attention has been given to the influence of the transition zone between aggregate and the cement matrix in several properties of the concrete [1]. Most of researches in this area have used conventional aggregate such as crushed rocks. The transition zone can be defined as the region between different materials or different phases, among which a contact area, denominated interface, exists. There is a consensus in the literature indicating that the transition zone constitute weak points in the structure of the concretes, clearly influencing the mechanical strength, elasticity modulus and permeability [2,3]. On the other hand, it is still not known to what extent the properties of the concrete can be improved through increments in the performance of the cement matrix in connection with the aggregate.

In the initial ages, the volume of voids present in the transition zone is larger than inside the cement matrix, due to a film of water that is formed around the coarse aggregate, contributing to the increase of the W/C. In this way, the growth of crystals in that area finds little opposition and the size and the concentration of the crystalline compositions, such as calcium hydroxide (portlandite - CH) and the etringgite increase, forming a more porous structure in the transition zone than in the cement matrix. The big calcium hydroxide crystals tend to form oriented layers that facilitate the appearance of microcracks. Such effects are responsible for the smaller strength of the transition zone in relation to the cement matrix [4,5].

The properties of the concrete can be improved due to physical or chemical processes that occur in the transition zone between the coarse aggregate and the cement matrix. The chemical processes are associated with this aggregate's pozzolanic activity and with the deposition of CH in voids of the transition zone, and the physical interactions are associated with the effect of "filtration" of the porous aggregate, and with the mechanical interlocking of these aggregates with the cement paste [1,4,6].

In the case of porous aggregates, it is necessary to consider its saturation degree. If the inert is not saturated, the water absorbed by the aggregate in the moment of the mixture of the concrete, with time, becomes available for the hydration of the grains of cement, still not hydrated. The great part of that additional hydration happens in the area of the aggregate - matrix interface, promoting a stronger bond between the aggregate and the matrix [5]. The properties of the cement matrix (located near by of the lightweight aggregate) can be improved due to an effect of "filtration" of the cement paste (viscous), where only the water enters the aggregate. This supplies the relative impermeabilization around the external pores of the lightweight aggregate, minimizing the absorption of the water and providing the hardening effect of the interface [1,6]. In the case of saturated porous aggregates, the aggregate behaves as a non porous aggregate and the phenomenon of adherence limits to mechanic interconnections in the interface [5].

The objective of this work is to evaluate the improvement of the transition zone between the expanded clay aggregate and the cement matrix in the LWAC by aggregate's pozzolanic activity.

8.2 EXPERIMENTAL PROCEDURE

In the present work an expanded clay was used as aggregate in LWAC and a crushed limestone was used in NWC. The same particle size distribution ranged from 6 to 15 mm was obtained for both aggregates. In the physical characterization the expanded clay presented high water absorption (30% at 24 h) and lower bulk density (460 kg/m³) in relation to limestone aggregate. The cement used was a Portland cement CPV (high initial strength) corresponding to the ASTM C 150, for not containing mineral admixtures, what could modify the chemical reactions in the transition zone. Specimens of both concretes were cast with the same mix proportions for an estimated compressive strength of 40 MPa. The only difference between them was the coarse aggregate used.

8.2.1 X-ray diffraction analysis

In the mineralogical characterization of the lightweight aggregate and concretes, the main present crystalline phases were determined using X-ray difraction technique. A model PW-3710 (CuKα radition, current of 30 mA and voltage of 40kV, scan rate 0,060º/seg) PHILIPS difratometer was used.

8.2.2 Activity Pozzolanic test

The pozzolanic activity of the powder adhered to the surface of the expanded clay, with the cement Portland CPV ARI was evaluated using physical and chemical methods.

8.2.2.1 Physical method

The analyses by physical method followed the specifications of NBR 5752 [7]. Three mortar specimens were molded with 35% substitution, in volume, of cement by the supposedly pozzolanic material and three specimens without substitution. The index of pozzolanic activity was evaluated by the percentile relationship between the average resistances to the axial compressive of the specimens with substitution and without substitution, at 28 days.

8.2.2.2 Chemical method

In this method, the pozzolanic activity was evaluated comparing the amount of present CH in the liquid phase in contact with the moisturized cement, with the amount of CH which could saturate an expedient of same alkalinity, according to recommendations of NBR 5753 [8].

8.2.3 Diffuse reflectance infrared Fourier transform spectrometry (DRIFTS)

The spectrometry analysis in the infrared identifies the presence of some types of structures of chemical connection, due to variations of energy caused by vibrational or rotational alterations of the molecules. This technique can be used in the qualitative and semi-quantitative determination of molecular species [9]. This analysis was used, to identify the presence of CH and to accomplish a semi-quantitative analysis, comparing the contents of the compouds found in LWAC and in NWC. The analyses were accomplished using diffuse reflectance involving the beam of infrared energy through the powdered sample, measuring the spectrum of the scattered radiation. A Perkin Elmer Spectrum 1000 spectometer was used, as well as molded KBr disks with the powder of the cement matrix removed from the transition zone.

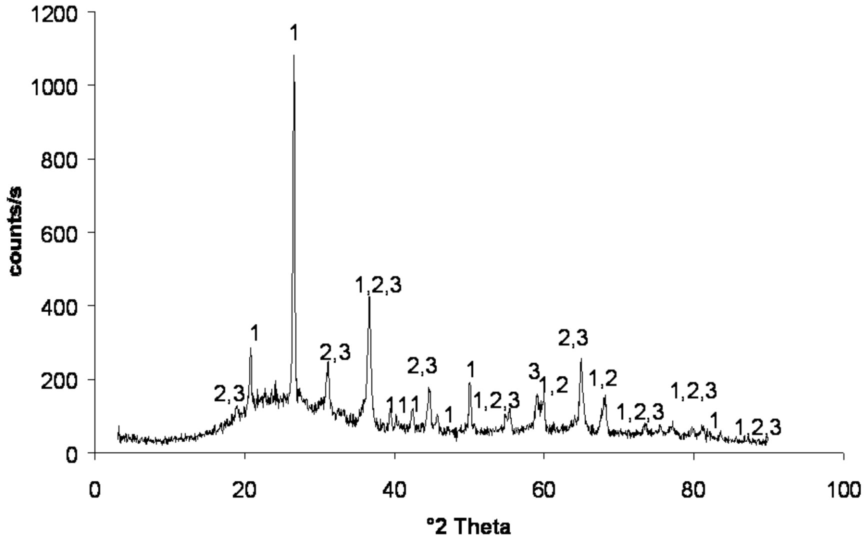
8.2.4 Scaning electron microscopy (SEM) analysis

The morphology of the expanded clay and transition zone between the coarse aggregates and the cement matrix were evaluated through the microstructrural analysis, using scanning electron microscopy (SEM). A microscope JSM-80 PHILIPS was used, being the samples covered with carbon film to be conductive. The images were obtained by secondary electrons.

8.3 RESULTS AND DISCUSSION

8.3.1 X - ray diffraction

The Figure 8.1 displays the diffratogram of the expanded clay powder with its main compounds obtained by X-ray diffraction. Analyzes of the expanded clay indicated the presence of quartz, silicates and spinel, responsible for the formation of the glass phase of this aggregate during the process of production of the expanded clay. In the analyzes of concretes by X-ray diffraction, the main compounds found in NWC were the dioxide silicon (SiO_2), calcium hydroxide ($Ca(OH)_2$), calcite ($CaCO_3$), and the hydrated calcium silicate ($Ca\ SiO_4\ 0{,}3H_2O$), while in LWAC the main compounds were the dioxide silicon (SiO_2), calcium hydroxide ($Ca(OH)_2$), magnesium aluminum oxide ($Mg\ Al_2O_4$), and the hydrated calcium silicate ($Ca\ SiO_4\ 0{,}3H_2O$).



1- SiO_2 - Silicon (α-Quartz);
2- $Mg(SiO_4)$ - Magnesium Silicate;
3- $MgAl_2O_4$ - Magnesium Aluminum Oxide (Spinel).

Figure 8. 1 – Spectrum of the expanded clay by X-ray diffraction.

8.3.2 Pozolanic activity

Table VIII.1 displays the results obtained by the chemical analysis of the expanded clay, LWAC and NWC. The results show that LWAC presents higher contents of SiO_2 and Al_2O_3 due to the expanded clay while NWC presents higher percentage CaO due to the limestone.

Table VIII. 1 – Composition of the expanded clay powder and concretes with estimated compressive strength of 40 MPa.

Oxids	Expanded Clay (%)	LWAC (%)	NWC (%)
CaO	0.23	18.44	35.13
SiO_2	64.21	52.52	31.32
Al_2O_3	11.48	8.86	2.83
Fe_2O_3	9.37	1.44	0.84
K_2O	4.22	2.06	0.89
MgO	3.43	0.82	0.27
Na_2O	0.41	0.23	0.09
TiO_2	0.37	-	-
S	0.03	-	-
LOI	0.96	13.20	26.21

According to the chemical composition of the expanded clay powder shown in the Table VIII.1, the sample presents a sum of the compositions (SiO_2 + Al_2O_3 + Fe_2O_3) around 85%, overcoming the minimum limit of 70% specified by NBR 12653 [10] so that the material may be considered pozzolanic.

The Figure 8.2 shows the graphic of the pozzolanic activity of the expanded clay powder, evaluated by chemical method at seven days of age.

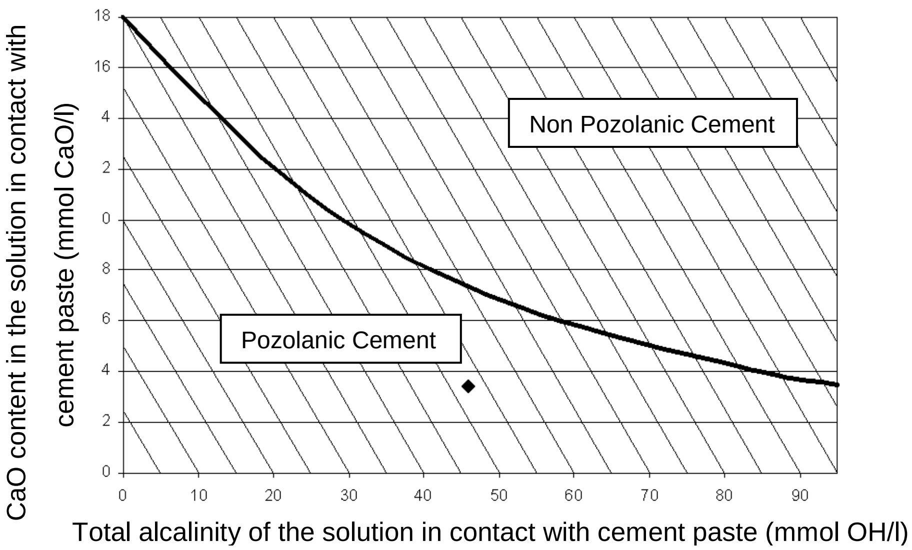


Figure 8. 2 - Graphic of the pozzolanic analysis of the expanded clay powder.

The result of the pozzolanic analysis of the expanded clay powder, by the chemical method, was below the curve limit, area regarded as a pozzolanic material's area. That result reveals that there was pozzolanic activity between the silicates of the powder of the lightweight aggregate grains and the CH of the cement matrix, forming the C-S-H (silicate of hydrated calcium). This indicates a probable occurrence of larger indexes of pozzolanic activity in LWAC when compared to the same activity in NWC. As the major part of that powder is adhered to the surface of the expanded clay, its reactivity can corroborate for the formation of an transition zone more denser and homogeneous in LWAC in relation that happens in NWC. That densification effect can contribute to a reduction of the permeability of LWAC, what would contribute to a larger durability of that concrete in relation to NWC.

Table VIII.2 displays the index of pozzolanic activity of the expanded clay powder, evaluated by the physical method. The results of Table VIII.2 show that powder presented an index of pozzolanic activity of 47%, therefore, inferior to the minimum index of 75%, presented by NBR12653. However this doesn't mean that the material does not possess pozzolanic properties, but that, the reactivity of that material when substituting the cement, did not reach the indexes specified for a significant influence in the compressive strength. The low index of pozzolanic activity of the expanded clay powder with the cement Portland may be related with the high crystallization degree (Fig. 8.1) and with the smaller specific surface of the powder (0.38 m²/g) in relation to the cement (1.2 m²/g). In spite of the specific surface of the clay powder being approximately 3 times smaller than the cement one, the amount of water needed to produce the mortar with normal consistence index (225 ± 5 mm) was the same.

Table VIII. 2 – Pozolanic activity evaluated by physical method.

Specimens	Water Demand (%)	Average Strength (MPa)	Standard Deviation (MPa)	pozzolanic activity (%)
Standard mortar	100	30.2	2.1	47
Mortar with substitution	100	14.3	0.7	

8.3.3 Evaluation of the CH content by DRIFTS

The Figure 8.3 displays the spectrum of the DRIFTS analyses with the structures of chemical ligament found in the samples of NWC and of LWAC. Table VIII.3 presents the results of the relationship between the portlandite and etringgite band, obtained by the spectrum of DRIFTS, for NWC and for LWAC.

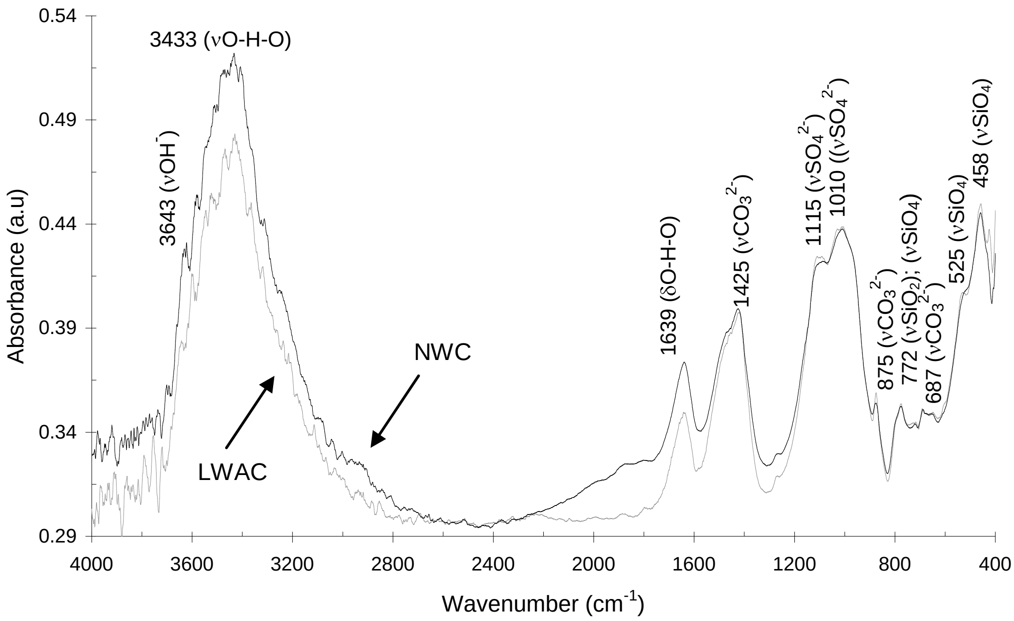


Figure 8. 3 – DRIFTS spectra of normal-weight and lightweight concretes samples. δ and ν indicate bending and stretching vibration respectively.

The band at 3643 cm^{-1} is assigned to the OH-group vibration of calcium hydroxide. The absorption peaks in 3433 and 1639 cm^{-1} are due to H_2O bending and stretching vibration respectively. The presence of the calcite mineral is assigned in 1425, 875 and 687 cm^{-1} bands. The broads in 1115 and 1010 $cm^{-}1$ are due to SO_4 vibration of ettringite and calcium sulphate dehydrate respectively. Quartz (SiO_2) and feldspar orthoclase ($KAlSi_3O_8$) are evident from the strong band in the spectrum at 772 cm^{-1}. These mineral are present in mineralogical composition of the sand of concretes. The SiO_4 stretching vibration of the silicates can be identify in 525 and 458 cm^{-1} bands [11,12].

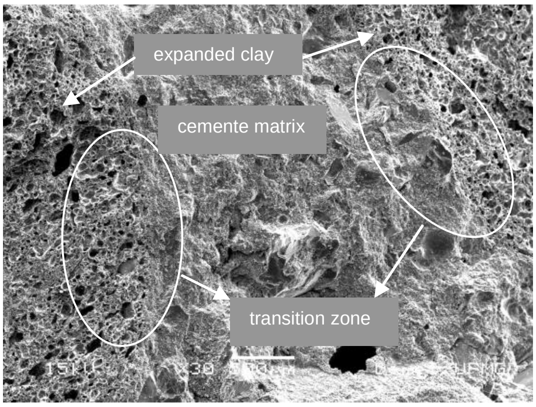
Table VIII. 3 – Bands relation between portlandite and etringgite in the NWC and LWAC.

Sample	Ordinate y (a.u)			Relative hight (a.u)		Bands relation
	Portlandite	Etringgite	Base line	Portlandite	Etringgite	
NWC	0.427969	0.422162	0.323824	0.104145	0.098338	1.06
LWAC	0.384015	0.424455	0.310872	0.073143	0.113583	0.64

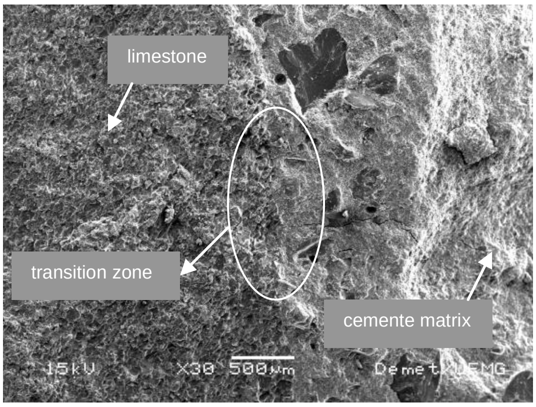
For the semi-quantitative evaluation of the portlandite, we use as reference the peak of the etringgite, once, the other main peaks would be related to the calcite and to the water, not representing a good reference, due to the presence of limestone crushed rock in NWC and to variations in the reactions of hydration of the concretes. The relative heights of the portlandite and etringgite bands were obtained using the heights of the peaks of these phases, in relation to a base line chosen arbitrarily in the graph. With this data, the relationship between the portlandite and etringgite bands was determined dividing the relative heights of those phases. It is observed, in Table VIII.3, that the relationship obtained between the portlandite and etriggite bands was smaller in LWAC in relation to NWC. That indicates, qualitatively, a smaller CH content in the transition zone between the coarse aggregate and the cement matrix in LWAC in relation to the NWC. That result confirms the hypothesis suggested in the pozzolanic activity analyses (Figure 8.2) that a larger index of pozzolanic activity occurs in the transition zone of LWAC in relation to the one in NWC.

8.3.3 Morphology of the transition zone by SEM

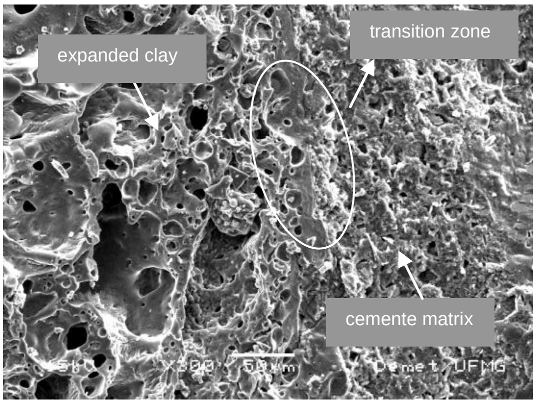
Figure 8.4 presents image analysis obtained by SEM, illustrating the morphology of the transition zone of the concretes having an estimated compressive strength of 40 MPa.



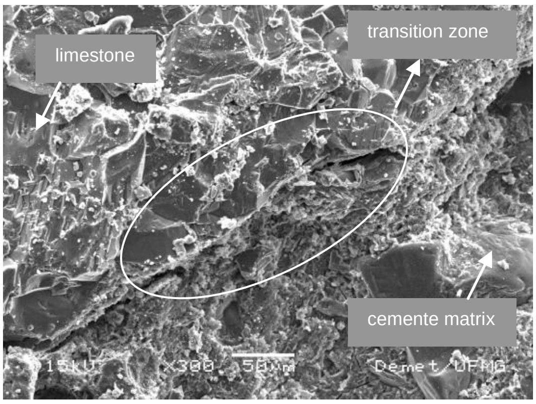
(a) lightweight concrete 40 MPa (30X)



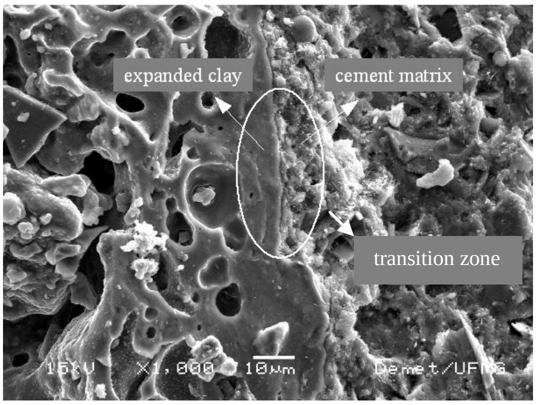
(b) normal-weight concrete 40MPa (30X)

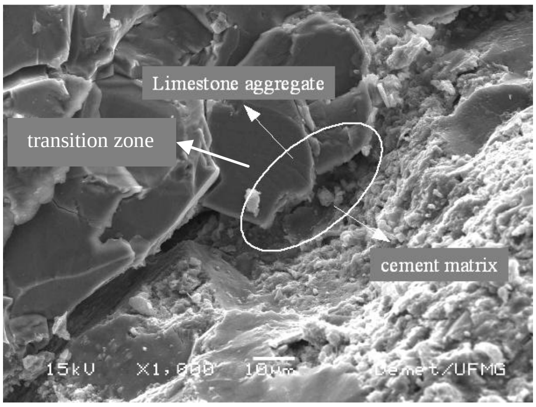


(c) lightweight Concrete - 40 MPa (300X)



(d) normal-weight concrete - 40 MPa (300X)



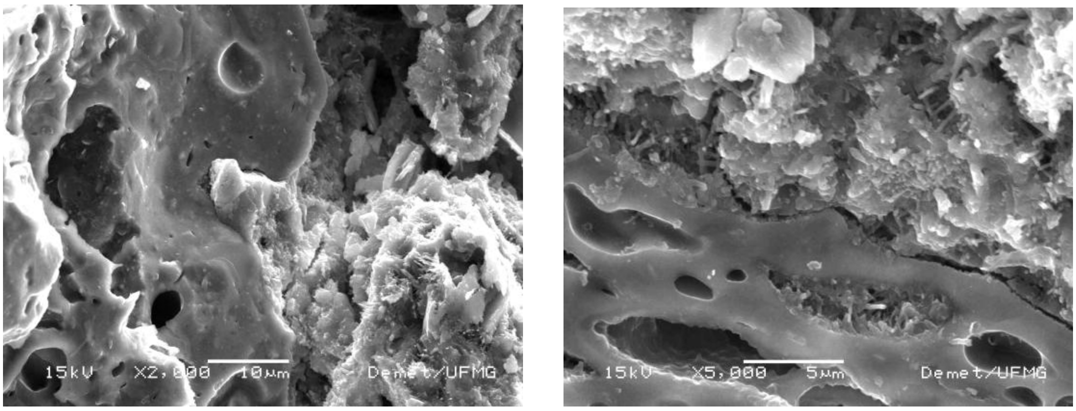


(e) lightweight Concrete - 40 MPa (1000X) (f) normal-weight concrete - 40 MPa (1000X)

Figure 8. 4 - Image analysis obtained by scanning electron microscopy.

As it had been expected, the transition zone for the NWC (Figure 8.4b) shows itself more porous and micro-cracking in relation to the LWAC (Figure 8 4a). It was observed that for the LWAC (Figure 8.4c) we cannot sharply distinguish the interface as in the NWC (Fig 8.4d), characterizing a transition zone denser in the LWAC. It was also observed a better adherence in the interface between the expanded clay and the cement matrix in the LWAC (Figures 8.4c, 8.4e) in relation to the interface between limestone aggregate and the matrix in the NWC (Figures 8.4b, 8.4f).

In the Figure 8.5a and 8.5b it can be observed the penetration of the cement paste and products of its hydration inside the shell of the pores of the expanded clay aggregate's surface, respectively, increasing the bond by mechanical interlocking. As the expanded clay presented high absorption, this aggregate will tend to absorb part of the water of the mixture, promoting an effect of filtration of the cement paste, in which the water will penetrate in the aggregate and the viscous part will be kept in its surface. The absorbed water can accomplish additional hydrations in the transition zone of the LWAC. This phenomenon may contribute for the formation of a denser transition zone with smaller micro-cracking incidence in LWAC when compared to the NWC.



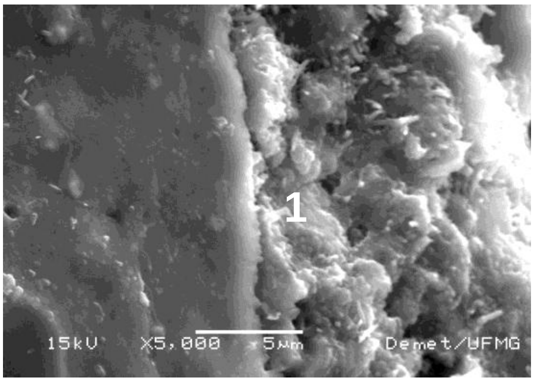
(a) (b)

Figure 8. 5 - Image analysis of the LWAC (a) penetration of the cement paste in the pores (2000X), (b) products of hydration inside the shell of the pores (5000X).

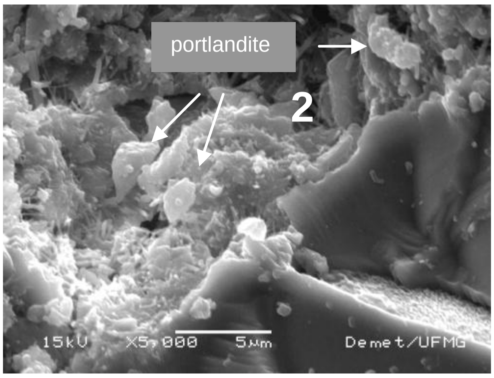
Table VIII.4 shows the chemical composition present in the points of Figure 8.6a 8.6b 8.6c and 8.6d, analyzed by EDS (energy dispersive spectrometry). In general, the elementary chemical analysis shows evidence a reduction of the contents of calcium and an increase of the silica contents in the interface between the expanded clay and the cement matrix in relation to that formed between the limestone aggregate and the cement matrix. It can be due to the aggregates mineralogy and phases formed in transition zone.

Table VIII. 4 - Chemical composition of the points in the interface between coarse aggregate and cement matrix.

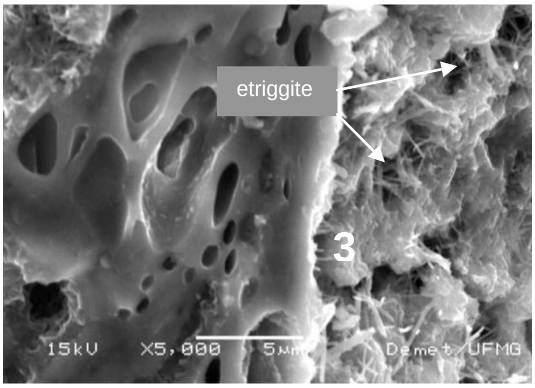
Interface	LWAC		NWC	
	Point 1	Point 3	Point 2	Point 4
CaO	43.87	44.10	78.93	85.93
SiO_2	26.32	28.72	8.93	6.45
Al_2O_3	11.69	9.27	3.49	2.16
SO_3	4.35	4.95	2.75	1.27
MgO	2.52	1.77	1.83	1.54
K_2O	1.67	5.32	1.78	1.01
Na_2O	0.56	0.77	1.33	0.80
TiO_2	0.23	0.26	0.59	0.33
SiO2/CaO	1.67	1.54	8.82	13.32



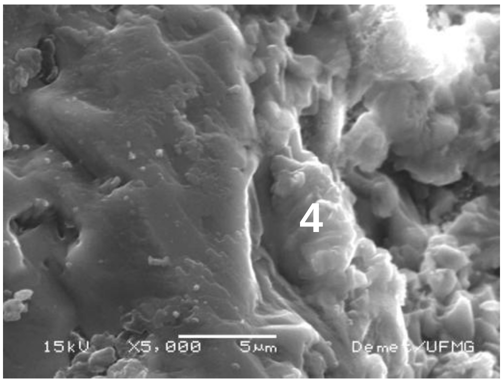
(a) lightweight Concrete – 40 MPa



(b) normal-weight concrete – 40 MPa



(c) lightweight Concrete – 40 MPa

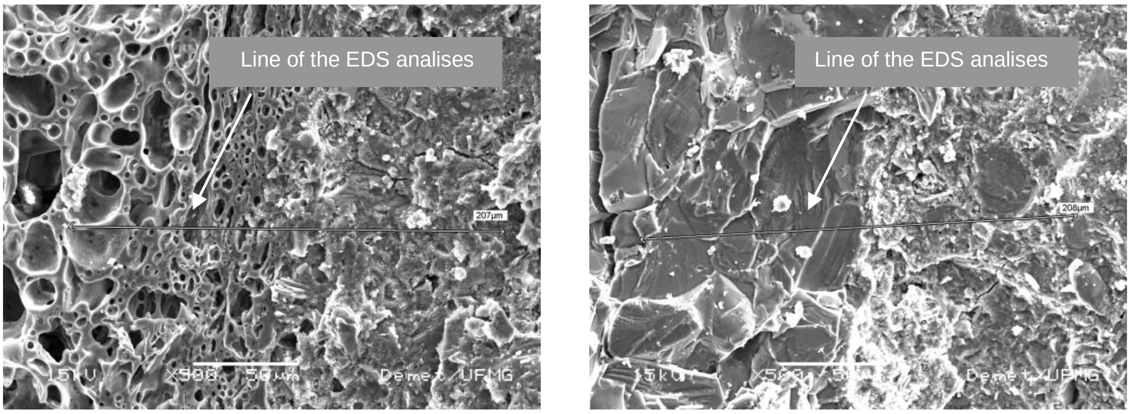


(d) normal-weight concrete – 40 MPa

Figure 8. 6 - Image analysis (5000X) obtained by scanning electron microscopy.

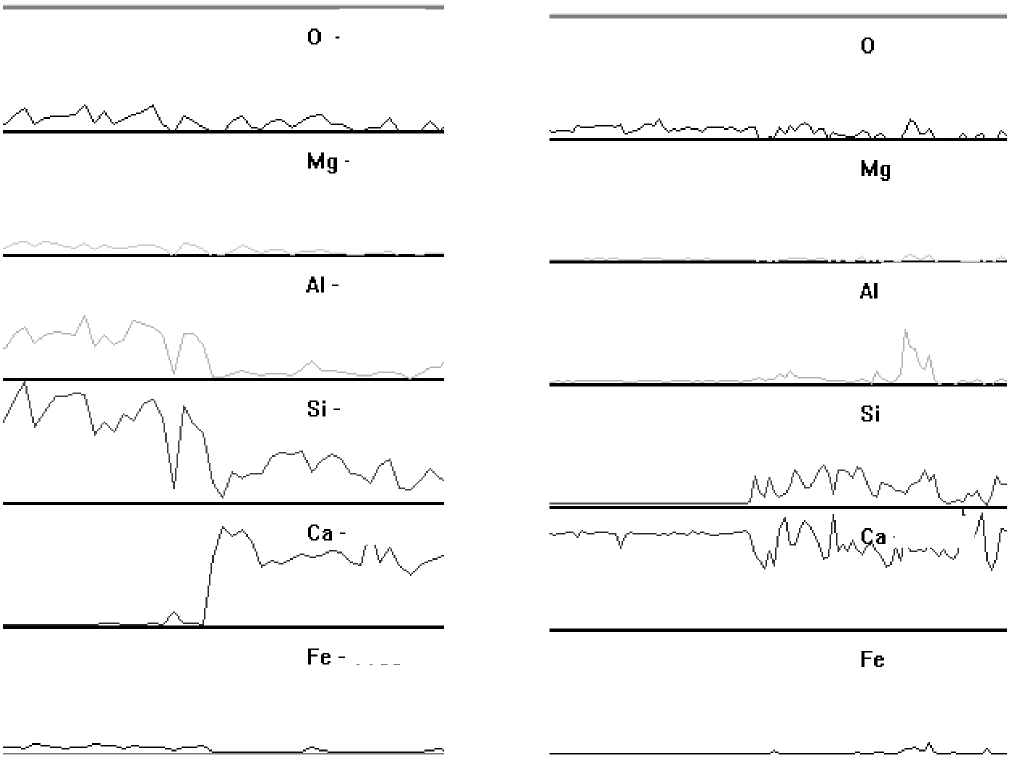
In Figures 8.6b and 8.6c the presence of portlandite and etringgite crystals can be observed in NWC and LWAC, respectively. The portlandite crystals have the hexagonal form with reduced thickness and they tend to appear in the first layers of the transition zone parallel to the aggregate's surface, forming a preferential orientation [5]. That orientation promotes the beginning of the propagation of micro-crack, which can contribute to a less resistant transition zone in NWC, when compared to the LWAC.

In Figure 8.7 images analysis of both concretes are displayed, indicating lines along which an elementary chemical analysis obtained by EDS was accomplished with graphs presented in Figure 8.8a and 8.8b.



(a) lightweight concrete – 40 MPa(500X) (b) normal-weight – 40 MPa (500X)

Figure 8. 7 – lines where elementary chemical analyses were accomplished.



(a) lightweight concrete – 40 MPa (b) normal-weight concrete – 40 MPa

Figure 8. 8 - Graphs of the EDS analysis along the lines.

The chemical analysis along the lines in the transition zone for the two concrete types shows from the coarse aggregate to the cement matrix, a reduction of the silicon and aluminum contents and an increase of the calcium content in the LWAC. For the NWC, the opposite can be observed: a reduction of the calcium content and increase of the silicon content. The results confirm previous evidences which was shown in Table VIII.4.

8.4 CONCLUSIONS

The powder adhered to the expanded clay presented pozzolanic properties that can be explained by the thinness of that powder, leading to a larger reactivity, and by the presence of silicates which react with the CH of the cement matrix, forming the C-S-H. That behavior indicates a probable occurrence of larger indexes of pozzolanic activity in LWAC corroborating for the formation of a denser and homogeneous transition area, and for a larger durability of that concrete in relation to NWC.

The relationship between the portlandite and etringgite bands obtained in the spectrum of DRIFT, was smaller for LWAC indicating smaller CH content in the transition zone between the coarse aggregate and the cement matrix in that concrete in relation to NWC. That result confirms the hypothesis that a larger index of pozzolanic activity happens in the transition area of LWAC in relation to the transition are of NWC.

The coarse aggregate - cement matrix interface is less evidenced for the LWAC in relation to the NWC, characterizing the largest bond between the expanded clay to the cement matrix. For porous or rough surface of the expanded clay, the cement paste or products of its hydration can penetrate inside the shell of the pores of the aggregate's surface, increasing the mechanical bond characterized in the LWAC.

In general, the elementary chemical analysis evidenced a reduction of the contents of calcium and an increase of the silica contents in the interface between the expanded clay and the cement matrix in the LWAC in relation to that formed between the limestone aggregate and the cement paste in NWC. This proportion can be related to the smallest formation of calcium hydroxide and to the biggest formation of hydrated calcium silicate, what promoted a densification of the transition zone in LWAC, corroborating for a higher durability of this concrete in relation to the NWC.

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CAPÍTULO 9 - Investigation of the Autogenous and Drying Shrinkage, and Micro-Cracks Formation in the Transition Zone of the Expanded Clay And Cement Matrix in Lightweight Concrete

Note: To be submitted to the journal Advanced Cement Based Materials.

Authors: Weber Guadagnin Moravia, Flávio A. dos Santos, Wander Luiz Vasconcelos.

Abstract

The knowledge presented on the literature regarding of the shrinkage is controversial when comparing this phenomenon in normal-weight concrete (NWC) and lightweight aggregate concrete (LWAC). The purpose of this article is investigate the autogenous and drying shrinkage in NWC and LWAC as well evaluated the micro-cracks formation in the transition zone between the coarse aggregate and the cement matrix in both concretes. Mercury Intrusion porosimetry, modulus of elasticity, autogenous and drying shrinkage methods were studied for the NWC and LWAC. Shrinkage cracking was investigated in the transition zone by scanning electron microscopy (SEM-EDS), to evaluate the effect of the autogenous and drying shrinkage. From the results it was able to predict the influence of the expanded clay in the shrinkage and micro-cracking on the transition zone of the LWAC. The LWAC presented a smaller incidence of micro-cracks and a smaller total shrinkage was observed in LWAC although it has presented larger drying shrinkage than NWC, in more advanced ages.

Keywords: lightweight concrete; shrinkage; micro-cracking; transition zone.

9.1 INTRODUCTION

The shrinkage is one of the main cracking causes in the concrete and its occurrence is associated to the durability of this material. Among the main factors that influence the retraction in concretes, we can mention: the mineralogy and the maximum dimension characteristic of the aggregates, the water/cement factor of the mixture, the elasticity modulus of the concrete, the transition zone between the coarse aggregate and the cement matrix, and the cure processes [1].

A consensus does not exist among researchers regarding the behavior of LWAC in relation to the shrinkage, when it is compared to the shrinkages of NWC. Some authors suggest that the use of lightweight aggregates in concretes results in larger shrinkages than those observed in NWC, while others, studying the shrinkage in the drying process in LWAC, found smaller shrinkages in relation to the obtained in NWC. That difference of results can be explained by the several types of light aggregates, with different raw material and production processes, resulting in aggregates with different behaviors.

The shrinkage in concrete structures is associated to dimensional alterations, with no type of loading and it corresponds to the combined action of its autogenous shrinkage, thermal shrinkage, drying shrinkage, and its shrinkage by carbon adding [2].

The autogenous shrinkage can be defined as the volume reduction of the concrete without loss or substance entrance, temperature variation or application of external forces. During the process of hydration of the cement hydrated compositions are formed with smaller volume than the sum of the initial volumes of the unhydrated cement and water, providing a reduction of the absolute volume of the concrete denominated of “contraction of Le Chatelier” or chemical shrinkage. The necessary consumption of water for the formation of those compositions causes a reduction of the relative humidity inside the concrete without mass loss (self-drying). This way, meniscuses in the capillary of the mortar are formed, which resulting efforts of the superficial stress of the water take to the autogenous shrinkage [2,3].

The shrinkage of thermal origin is associated to the reduction of the volume of the concrete during its cooling process, after the hydration reactions. The hydration of the cement Portland is always accompanied by liberation of heat that results in a temperature increase inside the concrete. After the setting time of the hydration reactions, the temperature of the concrete tends to balance itself to room temperature, generating stress that will be responsible for the shrinkage and micro-crack of thermal origins. The elevation of the temperature inside the concrete will depend on the consumption, type and thinness of the cement, of the speed of the chemical reactions, of the mineralogy aggregate's type, and of the volume of concrete applied [1,2].

The drying shrinkage consists of the volumetric reduction due to the loss of water during the drying process, when the concrete is submitted to ambient humidity below the saturation. The causes of the drying shrinkage are the same for the autogenous shrinkage, since the involved physical phenomenon is the same: appearance of the meniscus inside of the capillary, resulting in traction stress [3]. However, the mechanisms of water consumption contained in the capillary are different. While in the autogenous shrinkage the hydration reactions consume the capillary water (self-drying), in the hydraulic shrinkage the present water in the capillary evaporates (drying). Besides, the self-drying develops in a homogeneous and progressive way through the interior of the concrete, while the drying develops in a located way, mainly in the surface of the concrete [2].

The shrinkage by carbon adding can be defined, as the reduction of volume of the concrete due to the formation of the calcium carbonate, resulting from the reactions of the calcium hydroxide or of the of hydrated calcium silicate, with the carbon dioxide [1].

Analyzing the transition zone between the coarse aggregate and the cement matrix in the concretes, we can obtain important information regarding micro-cracking, in order to try to establish the influence of shrinkage in its formation. This way, the objective of this research is to study the autogenous shrinkage and the drying shrinkage in NWC and in LWAC and to evaluate the micro-crack incidence caused by that phenomenon in the transition zone between the coarse aggregate and the cement matrix.

9.2 EXPERIMENTAL PROCEDURE

It was used as coarse aggregate in LWAC, an expanded clay with sizes of grains between 6 and 15 mm, maximum dimension characteristic corresponding to 19 mm, porosity close to 18,54% and absorption of water, after 24 h, around 30%. A limestone with porosity close to 1% and with the same particle size distribution was used with aggregate in NWC. The cement used in both concretes was a Portland cement CPV (high initial strength) that corresponds to the American Standard ASTM C150 (CPIII). Specimens of NWC and LWAC were cast with the same proportions established and with water/cement ratio equal to 0.37, for the estimated compressive strength of 40 MPa.

9.2.1 Water absorption test

The water absorption of the aggregates, and its evolution at different time intervals, was evaluated following the method described in NBR 9937 [4]. The apparent porosity of the NWC and LWAC were established using mercury intrusion porosimetry.

9.2.2 Modulus of elasticity analysis

The secant elasticity modulus, was determined from the stress x strain curve of specimens of NWC and of LWAC, under axial compression, in agreement with NBR 8522 [5]. Three cylindrical specimens were studied (10 cm diameter and 20 cm height) for both concretes. The specimens were cured in the moist room and tested the age of 28 days.

The elasticity modulus of the aggregates was calculated from Equation 9.1 suggested by [6], that relates this property to the compressive strength and to the values of the elasticity modulus of the concretes.

$$E_c = -52 + 41.6\log(E_a) + 0.2 f_c \qquad \text{(Equation 9.1)}$$

Where:

E_a – elasticity modulus of the aggregate (GPa);
E_c – elasticity modulus of the concrete (GPa);
f_c – compressive strength of the concrete (MPa).

For determination of the compressive strength, cylindrical specimens were molded (diameter of 10 cm and height of 20 cm), and tested in agreement with NBR 5739 [7], corresponding to the American standard ASTM C 39.

9.2.3 Shrinkage test

The phenomenon of the shrinkage was evaluated in NWC and in LWAC from tests in the specimens of those concretes, where it was determined the autogenous shrinkage and the drying shrinkage.

9.2.3.1 Autogenous shrinkage test

The autogenous shrinkage was determined following the proceedings of the international workshop by JCI [8]. It was molded three prismatic specimens for NWC and three for LWAC, with dimensions of 10 x 10 x 40 cm (Figure 9.1). The extremities of the molds were covered with polystyrene sheet (thickness 3 mm), while the bottom and the lateral faces were covered with polyester film (thickness 1 mm), so that the specimens were not in contact with the mold and that free movement were not restrained. The top of the molds they were sealed by aluminum sheet and stored in a room at temperature of 22°C and a relative humidity of 58%. Changes in the length of the specimens were measured in each extremity by dial micrometer at 1, 2, 4 and 6 days.

Figure 9. 1 – Autogenous shrinkage test

It was utilized the Equation 9.2 to calculate the length change by shrinkage.

$$\Delta l = \frac{(X_{ia} - X_{0a}) + (X_{ib} - X_{0b})}{l} \quad \text{(Equation 9.2)}$$

Were:

Δl – length change;

l – distance between the innermost ends of gauge plugs;

X_{0a}, X_{0b} – Initial reading of dial gauge;

X_{ia}, X_{ib} – reading of dial gauge at time i.

9.2.3.3 Drying shrinkage test

The drying shrinkage of the concretes was measured following the recommendations of Mercosul norm NM 131 [9] that corresponds to the American Standard ASTM C 490. It was molded 3 specimens for both concretes, cured in saturated lime water (chalk) for 28 days. The Figure 9.2a shows the reference bar used as pattern and the prismatic specimens with dimensions of 7 x 7 x 28,5 cm, and Figure 9.2b shows the support for the reading of the measures using a dial micrometer.

(a) (b)

Figure 9. 2 - (a) Pattern bar and prismatic specimens (b) support for the reading of the drying shrinkage.

The calculation of the length variation of the specimens was accomplished through the following Equation 9.3:

$$\Delta L = \frac{(L_{xi} - L_i)}{L} \times 100 \qquad \text{(Equation 9.3)}$$

Where:

L_i – initial reading of the length of the specimens (mm);

L_{xi} – other readings of the length, done in pre-determined intervals of time (mm);

L – free internal distance among the pins (250 mm - adopted value).

This calculation supplies the variation measure of lineal length in percentage; however, this unit hinders the analysis of the results. In this study, it was used the micro-strain unit (mm/mm x 10^{-6}), facilitating the analysis and the comparison of the results with other investigations.

9.2.4 Scanning electron microscopy (SEM)

The formation of the micro-cracks in the transition zone between the coarse aggregate and cement matrix in the concretes was investigated through the image analysis, using scanning electron microscopy (SEM). A microscope JSM-80 PHILIPS was used, being the samples covered with carbon film to be conductive.

9.3. RESULTS AND DISCUSSION

9.3.1 Water absorption

Table IX.1 shows the absorption of water of the aggregates and the results obtained in the porosimetry analysis by mercury intrusion for NWC and LWAC.

Table IX. 1 - Water absorption of the aggregates and porosity of the analyzed concretes.

Water Absorption (%)					
Period	5 min.	15 min.	30 min.	60 min.	24 hs
Expanded clay	15	15	20	25	30
Limestone	0	0	0	1	1

Mercury Intrusion porosimetry			
Specimes	Total Pores Area (m2/g)	Average Pores Diameter (μm)	Apparent Porosity (%)
NWC	0.01	1.31	1.00
LWAC	3.12	0.22	18.54

It can be observed in the table above that the expanded clay presented high absorption of water in relation to the limestone. The forms the water is found inside the concrete and the degree of difficulty which it can be removed, have significant influence in the shrinkage [3]. Therefore, the absorption of the water by the expanded clay, during the mixture of the concrete, may hinder its evaporation and contribute to smaller shrinkage values in the drying process in LWAC in relation to NWC, until the water is eliminated in more advanced ages.

For capillary between 0.005 and 0.05 μm, the evaporation of the water can cause shrinkage in larger intensity [1]. As in LWAC the average diameter of the pores was below the obtained for NWC, indicating larger presence of pores with smaller diameters in LWAC. It is believed that LWAC can be more susceptible to the effects of the drying shrinkage.

9.3.2 Elasticity modulus

In Table IX.2 the values of the elasticity modulus of the aggregates and of the concretes dosed for an estimate strength of 40 MPa are shown.

Table IX. 2 – Elasticity modulus of concretes and aggregates.

Estimated Compressive strength (MPa)	Specimes	Elasticity modulus of concrete (GPa)	Aggregate	Elasticity modulus of aggregate (GPa)
46.6	NWC	25.1	limestone	42.6
33.4	LWAC	16.0	expanded clay	29.8

The results obtained for the static elasticity modulus of LWAC were between 15 GPa and 17 GPa, being in the medium third of the values obtained for NWC, according to the results found by other authors [10,11]. The smallest elasticity modulus of LWAC was influenced by the smallest modulus of the expanded clay in relation to the limestone aggregate. That result evidences the largest capacity of LWAC to absorb small deformations as those caused by shrinkage efforts, which reduces the internal stress and reduces the micro-cracks formation in this concrete, in relation to NWC.

9.3.3 Autogenous shrinkage

The Figure 9.3 shows the graphic obtained for the autogenous shrinkage strain of the specimens of NWC and LWAC, and the Table IX.3 present the results for the autogenous shrinkage considering 24 h and 48 h of age.

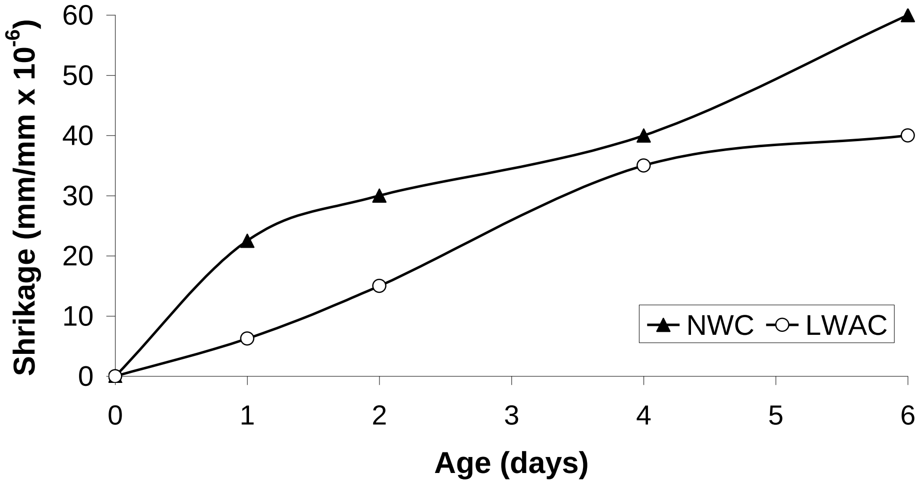


Figure 9. 3 – Graphic of the autogenous shrinkage strain.

Table IX. 3 - Results of the autogenous shrinkage.

Specimen	Time (h)	Left reading (mm)	Right reading (mm)	Total shrikage (mm)
NWC	24	0.005	0.004	0.009
LWAC	24	0.001	0.002	0.003

It can be observed in the table above that LWAC presented smaller values of autogenous shrinkage when compared to the values obtained in NWC. The expanded clay can act as a reservoir of water, promoting an internal cure and a smaller autogenous shrinkage in LWAC in relation to NWC [12]. It is important to stand out, that when the autogenous shrinkage is measured; the displacements related to the thermal shrinkage may also be included in those results, which happen simultaneously to the autogenous shrinkage [13]. As LWAC presents a better thermal performance in relation to NWC (Chapter 4 and 5), that might also have contributed to its smallest autogenous shrinkage. However, the main reason should be related to the water flow caused by the suction of the expanded clay the first ages, to replace the difference of concentration of existent water between its pores and the mortar. That flow will fill out the capillary of the mortar, mainly in the transition zone, which reduces the formation of meniscuses in its interior, avoiding the appearance of traction stress, responsible for the autogenous shrinkage.

9.3.4 Drying shrinkage

The Figure 9.4 displays the drying shrinkage strain in a time function for the specimens of NWC and LWAC.

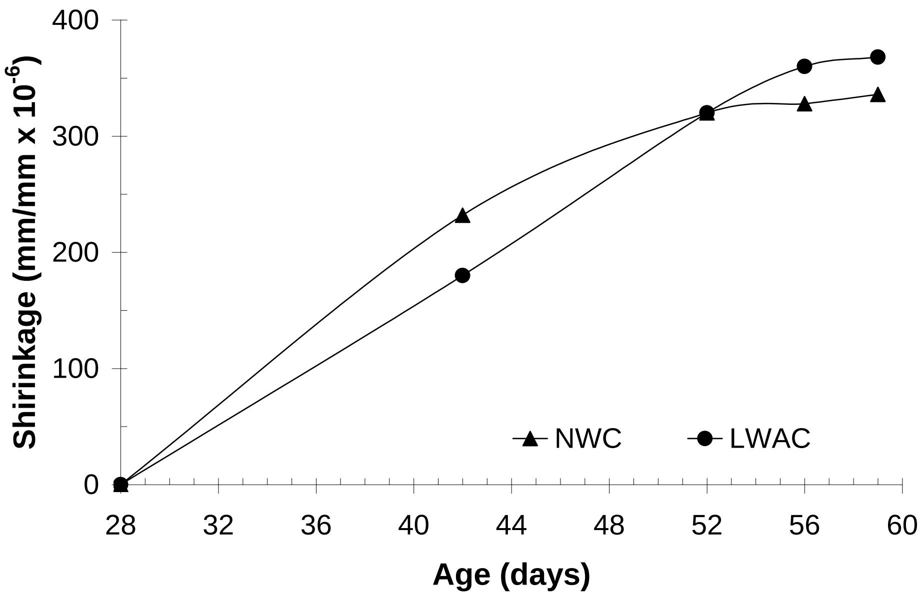
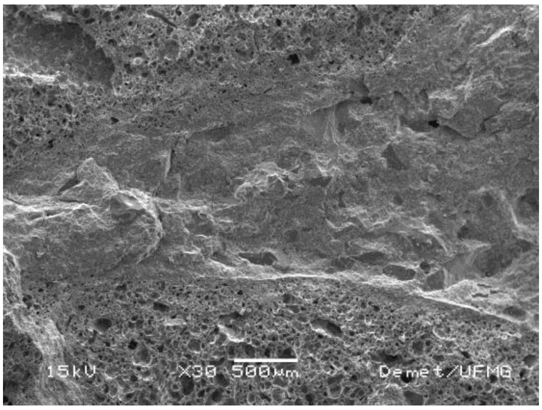


Figure 9. 4 – Graphic of the drying shrinkage strain.

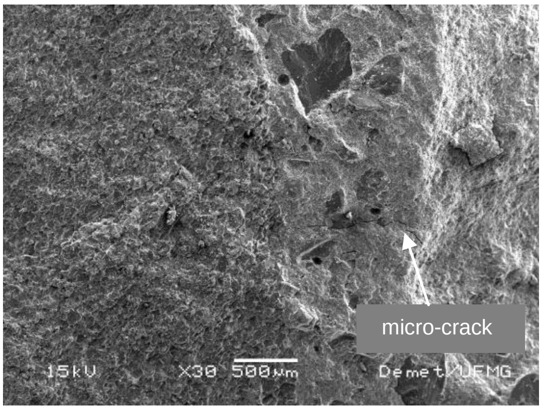
LWAC presented smaller drying shrinkage values until the age of 52 days, when both concretes had shrinkage of 320 micro-strains, which corresponded to a variation of lineal length of 0.08 mm. After that age, LWAC started to present larger drying shrinkage values in relation to NWC, what might have been due to the liberation of the absorbed water by the expanded clay in the moment of the mixture. The phenomenon of liberation of absorbed water is responsible for the formation and deposition of CH in the transition zone and it becomes effective after 28 days of age [14]. As the largest drying shrinkage of the LWAC was observed in older stages, this cn mean that in the initial ages, considered critical for the appearance of micro-crack, LWAC was not very requested which can take to a better performance and consequently larger durability of this concrete in relation to NWC.

9.3.5 Evaluation of the micro-cracks by SEM

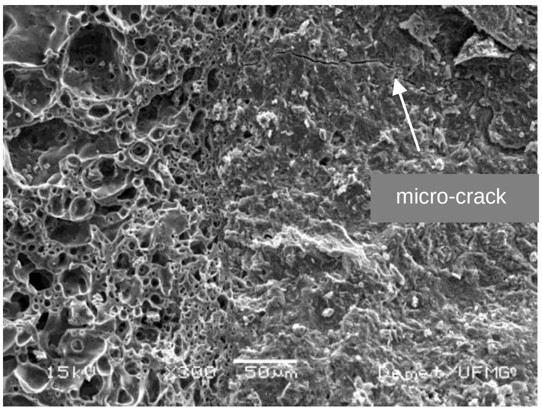
The transition zone is the region where the cracks start to happen. The Figure 9.5 shows image analysis done to evaluate the micro-cracking formation in the transition zone between the coarse aggregate and the cement matrix in NWC and in LWAC. In Figure 9.5b the formation is observed from a perpendicular micro-crack to the interface between the limestone and the mortar in NWC, while in Figure 9.5a, for the same enlargement (30X), the formation of micro-crack was not observed in LWAC. Already in Figure 9.5c the formation of a micro-crack is verified in the transition zone between the expanded clay and the mortar in LWAC, while in Figure 9.5d, fractures are observed, probably, of a micro-crack formed in the mortar during the shrinkage, and of the preferential orientation plains of the calcareous crushed rock. For greater enlargements, Figure 9.5e and 9.5f, the micro-crack formation is observed in both concretes. The observed cracks were formed perpendicularly to the interface of the aggregates, probably due tensile stresses, characteristic of the shrinkage.



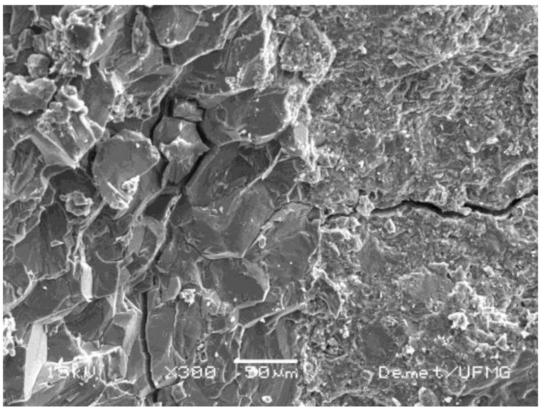
(a) lightweight concrete (30X)

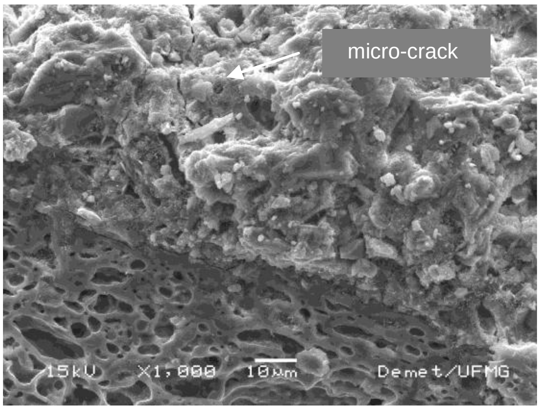


(b) Normal-weight concrete (30X)

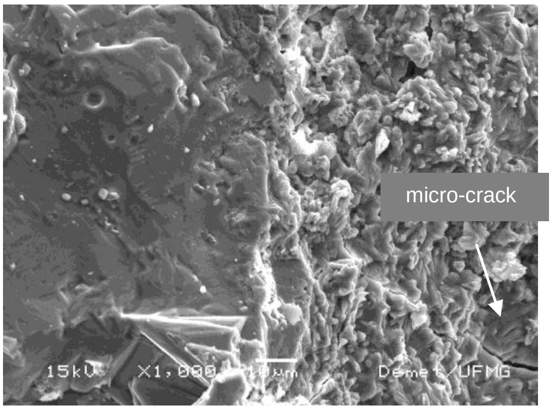


(c) lightweight concrete (300X)


(d) Normal-weight concrete (300X)



(e) lightweight concrete (1000X)



(f) Normal-weight concrete (1000X)

Figure 9. 5 - Image analysis obtained by scanning electron microscopy**.**

Figure 9.6 displays an image with the interfaces between the cement matrix and the two aggregate types.

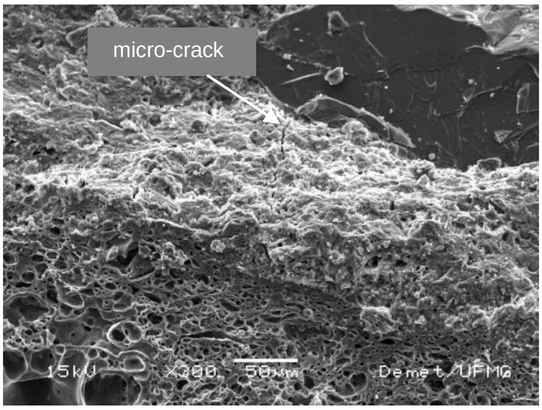


Figure 9. 6 - Transition zone of the aggregates with cement matrix.

It is observed in the illustration above, the presence of a micro-crack in the transition zone between the limestone aggregate and the cement matrix, while the same was not observed in the transition zone between the expanded clay and the matrix, indicating, probably, that the areas of transition of LWAC are less susceptible to the formation of fissures in relation to NWC.

9.4 CONCLUSIONS

The smallest autogenous shrinkage in LWAC, in relation to NWC, may be related to the water flow that was established in the first ages, due to the absorption by the expanded clay, that contributed to the filling of the capillary pores of the mortar with water, reducing the formation of meniscuses and the effects of the superficial stress of the water in the interior of the capillaries.

The absorption of water by the expanded clay, during the mixture of the concrete, may hinder its evaporation and contribute to smaller drying shrinkage values in the LWAC in relation to NWC, until that this water is eliminated. The liberation of the absorbed water by the expanded clay, in more advanced ages, might have been the responsible factor for the largest drying shrinkage in the LWAC, after 52 days of age.

The smallest value of the average pore diameter of LWAC in relation to NWC, indicates a larger presence of capillary with smaller diameters in that concrete, which might have contributed to the largest shrinkage in the drying process in LWAC.

The smallest elasticity modulus of LWAC, when compared to NWC, indicates a better capacity of deformation of the first when submitted to small efforts, which might have contributed to a smaller micro-crack incidence and smaller amounts of total shrinkage in LWAC. This behavior contributes to a larger durability of LWAC in relation to NWC.

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CAPÍTULO 10 - Stereological Parameters of the Macrostructure and Microstructure Models of the lightweight Concrete with Expanded Clay Aggregates

Note: To be submitted to the journal Cement and Concrete Research.

Authors: Weber Guadagnin Moravia, Wander Luiz Vasconcelos.

Abstract

This paper aims at studying the stereological parameters and their applications in the characterization of the macrostructures of the normal-weight concrete (NWC) and of the lightweight concrete (LWAC), as well as to evaluate the microstructure of those concretes to propose models of the transition area between the coarse aggregate and the cement matrix of NWC and LWAC. To evaluate the stereological parameters of the concretes it was used the Quantikov program. Graphs of distribution of sizes of grains were also obtained. The results were compared with the particle size distribution analysis of the aggregates used in the concretes. The stereological parameters were shown as a good tool for the characterization of concretes, and the models of transition area proposed, precisely represent the differences verified in those areas in NWC and in LWAC.

Keywords: lightweight concrete, estereolgical parameters, transition zone models.

10.1 INTRODUCTION

Analyzing parameters macrostructural and microstructural in heterogeneous materials as the concrete it is possible to obtain important information regarding the behavior of this material and try to establish the influence of these parameters in the properties of the concrete.

Physical characteristics of the aggregate, such as size distribution, bulk density, superficial area of the grains, forms and superficial texture, determine important properties of the concrete in the fresh and hardened states. Some of these macro structural parameters can be obtained by stereology. Stereology is a method that makes it possible to deduce structural parameters in three dimensions starting from two-dimensional parameters obtained in sections of the material, applying mathematical formulas based on geometric probability (area/volume) [1].

A micro structural study of the concretes allows evaluate the porosity, distribution of the phases, and the morphology of the transition zones. A Figure 10.1 illustrates the schematic model of the transition zone between the coarse aggregate and the cement matrix, as well as the distribution of the main phases present [2]. This model served as parameter for the proposition of a transition zone model to the lightweight concrete, presented in this paper.

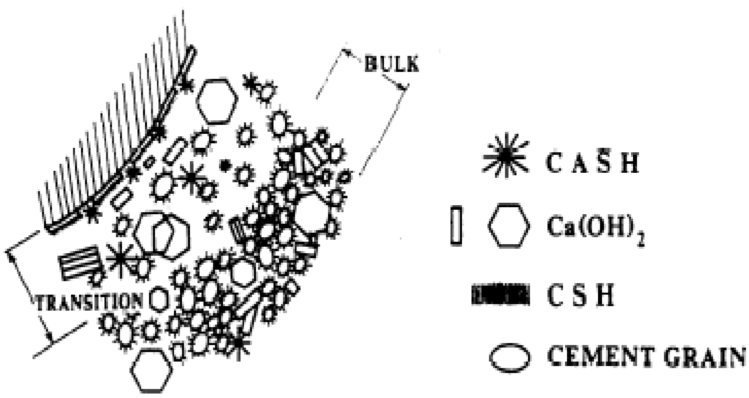


Figure 10. 1 - Transition zone between coarse aggregate and cement matrix. Source: ZANG e GJϕRV, (1991).

The objective of this work is to characterize the macrostructure of the grains of expanded clay distributed in the Portland cement matrix, using stereological parameters, seeking to define correlations with the properties of the lightweight concrete. Other objectives of this work are to suggest models for the transition zone, between the coarse aggregate and the cement matrix, of the normal-weight concrete (NWC) and of the lightweight concrete (LWAC), based on microstructural parameters studied in these concretes.

10.2 EXPERIMENTAL PROCEDURE

In the present work an expanded clay was used as coarse aggregate in LWAC. It was evaluated the particle size distribution of this aggregate according to NBR 7217 [3]. A limestone with a particle size distribution compatible to that observed in the expanded clay was used in normal-weight concrete (NWC). The concrete mixture proportions were determined according to IPT/USP method [4]. This method is based on the obtaining of the mixture proportions of concrete that provide a requested consistence and a average compressive strength (fcj) in **j** days of age. As dosage parameter a mortar content of 60% for both concretes was used.

10.2.1 Stereological analisis

In the obtaining of the stereological parameters the Quantikov program was used. It combines the digital image analyzer with stereometric quantification techniques based in the Saltykov method [5], which assumes that the grains and pores are spheres. That method consists of the counting of the number of intersections of a drawn mesh, with the element we want to evaluate. Digital images were made of the prismatic traverse sections of the specimens with dimensions of 7 x 7 cm. The images were treated in the program to enhance their details and later they were segmented. The segmentation consists of the transformation (binarization) of the image in black and white tones, which allows the differentiation of the element to be processed, for the determination of the geometric, metric and morphologic parameters [6].

A quantitative evaluation of the metric parameters was made:

Volume fraction (Vv) - reports the total volume of aggregates in three dimensional features, per concrete volume unit;

Surface area per volume unit (Sv) – reports the total superficial area of grains of the aggregates in three dimensions per concrete volume unit;

Average lineal intercept (λ) - number of intersections per unit of length.

A qualitative evaluation of the morphologic parameters was made:

Form factor - evaluates the degree of roundness of the grains;

Aspect reason - indicates the reason between the largest and smallest dimension of the grain.

Graphs of distribution of sizes of grains were also obtained. The results were compared with the particle size distribution of the aggregates used in the concretes.

10.2.2 Microestructural characterization

The apparent porosity of the expanded clay, limestone aggregates and concretes were established using mercury intrusion porosimetry. For the porosity concrete tests, cylindrical specimens (diameter of 20 mm and height of 25 mm, using aggregates with dimension of 5 mm) were tested at 28 days.

The morphology of the internal surface and the exposed surface of the grains of expanded clay were analyzed by the scanning electron microscopy (SEM). A PHILIPS, model JSM-80 microscope was used.

10.3 RESULTS AND DISCUSSION

10.3.1 Particle size distribution

Table X.1 presents the results of the particle size distribution of the coarse aggregates utilized in this work.

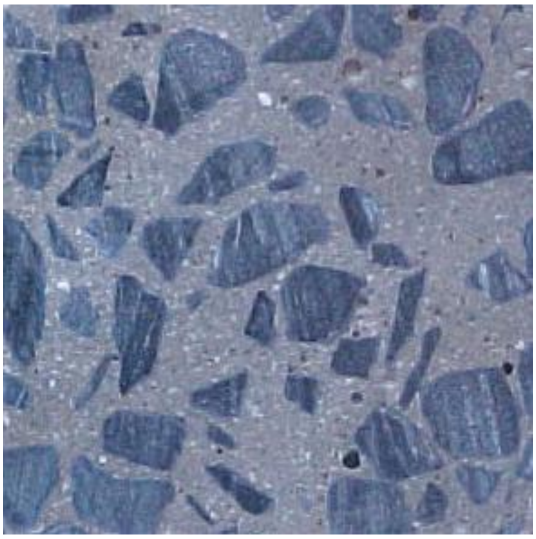
Table X. 1 – Particle size distribution analysis of the coarse aggregates.

Size (mm)	Material retained (g)	Cum retained (%)	Cum passing (%)
19	0	0	0
12.5	433	9	9
9.5	2553	51	60
6.3	1520	30	90
4.8	393	8	98
Pan	100	2	100
Total	5000	100	
Maximum dimension characteristic (mm)		19	
Fineness modulus		6.48	

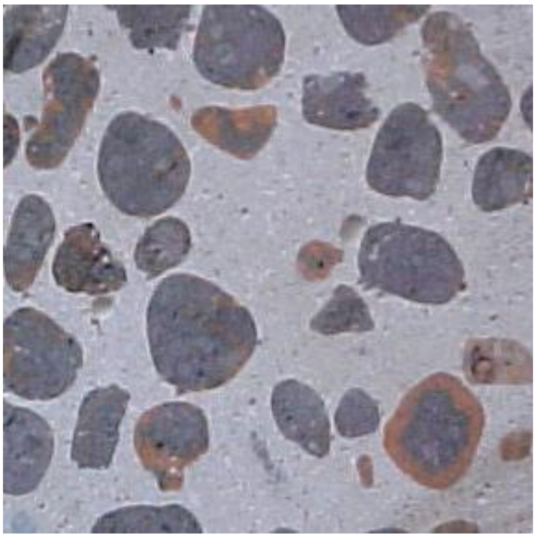
Based in the particle size analysis of the coarse aggregate it can be observed that the expanded clay possesses maximum dimension characteristic of 19 mm, and average dimension of the grains between 4.8 and 6.3 mm.

10.3.2 Treatment images

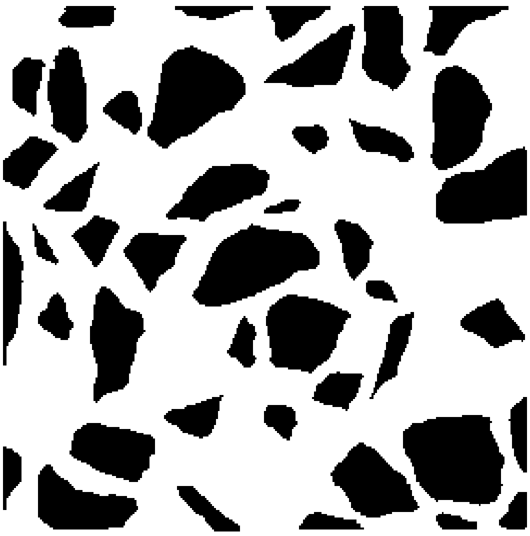
Illustration 9.2a and 9.2b display the digital images of the traverse sections of the prismatic specimens of NWC and of LWAC, respectively, while the Illustration 9.2c and 9.2d display the segmented images of those sections after the treatment in the Quantikov program.



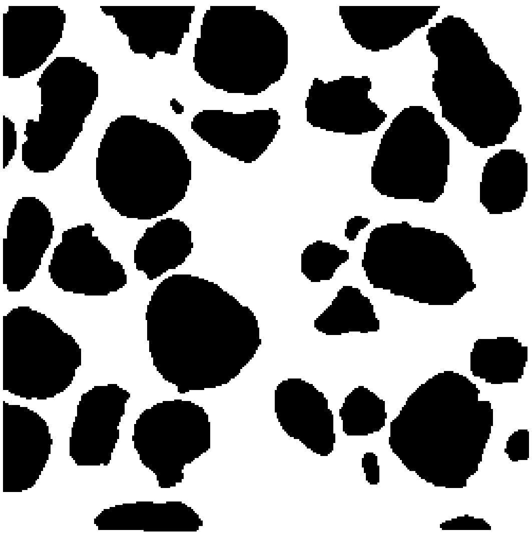
(a) image of the transversal section of NWC



(b) image of the tranversal section of LWAC



(c) segmented image of the section of NWC



(d) segmented image of the section of LWAC

Figure 10. 2 – images used to evaluat the stereological parameters.

10.3.3 Geometrics parameters

Table X.2 displays the results of the geometric parameters obtained in the analysis of the sections of NWC and of LWAC.

Table X. 2 – Geometric parameters of the aggregates of the NWC and of the LWAC.

Geometric parameters	Specimens		Standard deviation	
	NWC	LWAC	NWC	LWAC
average area of the grains (mm²)	36.04	62.25	29.15	43.44
larger area of the grains (mm²)	119.38	169.99	-	-
smaller area of the grains (mm²)	6.62	2.67	-	-
average perimeter of the grains (mm)	21.03	24.06	8.62	10.46
average diameter of the grains (mm)	6.29	8.28	2.53	3.33
area of the grains / total area (%)	34.55	43.91	-	-

For the analyzed images, the area of the grains of calcareous crushed rock in the section of NWC corresponded to 35% of the total area, while in LWAC, the area obtained for the grains of expanded clay was around 44% of the total area. Those results indicate that the mortar areas correspond to 65% and 56% of the area of the NWC and LWAC sections, respectively. It was verified that these results approached of the mortar content (60%) adopted in the dosage of both concretes. The differences observed between the mortar areas obtained and the mortar content adopted may be related to the segregation of the aggregates during the thickening of the concrete. The high deviation pattern of the average area of the grains, was due to the great variation in the distribution of sizes of grains, common characteristic of the aggregates used in concretes. The expanded clay presented an average perimeter slightly larger than the calcareous crushed rock, probably due to the round shape of their grains. Also, a structure of grains with average diameter of 6.29 mm for NWC and of 8.28 mm for LWAC was observed. The value calculated by the program for the average diameter of the grains of crushed rock approached, greatly, to the values obtained by the particle size distribution analysis (table X.1).

10.3.4 Stereologics parameters

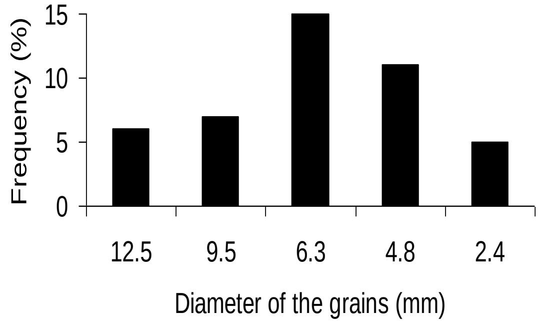
Table X.3 displays the results of the stereological, metric and morphological parameters obtained in the analysis of the sections of NWC and of LWAC.

Table X. 3 – Stereological parameters of the NWC and f the LWAC.

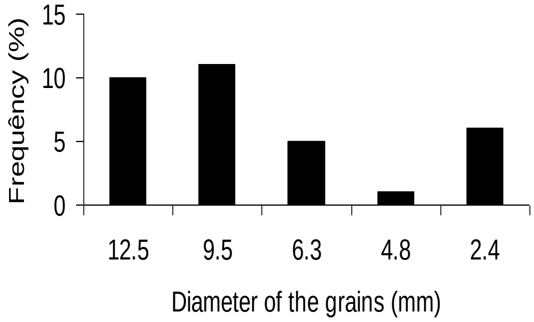
Stereological parameters		Specimens	
		NWC	LWAC
metrics	Sv - surface area per volume unit (mm^2/mm^3)	0.3	0.3
	λ - average intercept (mm)	6.08	7.75
	Vv - volume fraction (%)	45	58
morphological	form factor (4π A/P^2)	0.86	0.96
	aspect reason (d_{max}/d_{min})	2.21	1.25

The superficial area of the aggregates per volume unit was the same for NWC and for LWAC. The average intercept, average distance from the interface to the interface of the grains, was slightly superior in LWAC when compared to NWC. Although the volume of aggregates has been the same in both concretes, the values obtained for the volumetric fraction differed, and the volume of aggregates in NWC was smaller than the obtained in LWAC. This may be due to the difficulty of obtaining a representative section. The form factor of the expanded clay was closer to 1, which indicates the largest roundness of that aggregate's grain in relation to the calcareous crushed rock. For the aspect reason, values closer of 1 indicate symmetry in the dimensions of the particle, while values superior to 2 are characteristic of lamellar forms. The results obtained for the aspect reason of the aggregates used in the concretes confirm the round form of the expanded clay and the prolonged form of the calcareous crushed rock. If it was considered that in concretes with aggregates with larger roundness degree there is a larger probability of the rupture plans split up a larger area of these aggregates, the round form of the expanded clay may be one of the responsible factors for the smaller mechanic performance of LWAC in relation to NWC (Chapter 3), once that aggregate presents smaller mechanical strength when compared to the limestone.

Illustration 9.3 displays the graphs with the distributions of grain sizes of the limestone and of the expanded clay in NWC and in LWAC, respectively.



(a)



(b)

Figure 10. 3 - Distributions of grain sizes of the limestone aggregates (a) and of the expanded clay (b).

The distribution of grain sizes evaluated by the Quantikov program, showed that the aggregates possess diameters varying from 2.4 to 12.5 mm, with larger frequency of sizes in the strip from 6.3 to 9.5 mm. These results are in agreement with obtained in the distribution particle size analysis by sieving. The differences observed in the frequency of diameters of grains of the analyzed sections may be related to the adopted sampling and the segregation of the aggregates during the process of homogenization of the concretes.

10.3.5 Mercury intrusion porosimetry

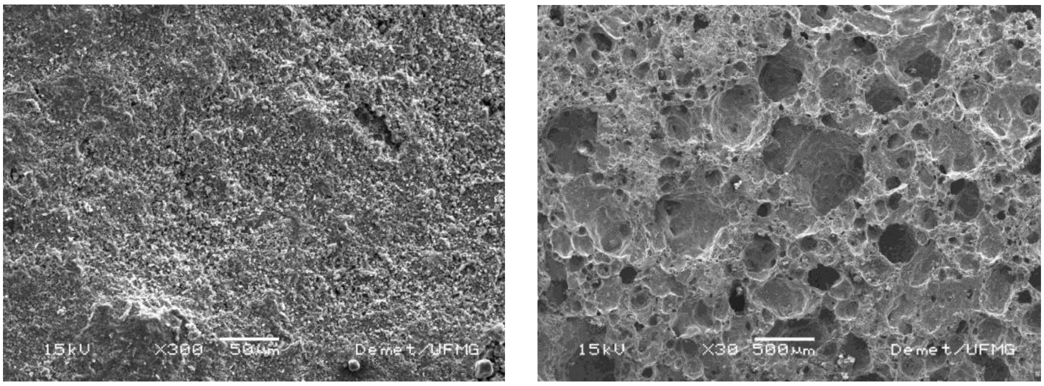
In Table X.4, the results of the mercury intrusion porosimetry are presented for the limestone and expanded clay aggregate, NWC and LWAC. The lightweight aggregate presents a larger apparent porosity than the limestone aggregates, what contributes to a higher porosity in the LWAC when compared with NWC.

Table X. 4 - Results of the porosimetry for the aggregates and concretes.

Samples	Total Pores Area (m^2/g)	Average Pores Diameter (μm)	Apparent Porosity (%)
Limestone Aggregate	0.010	1.3100	1.00
Expanded Clay Aggregate	3.116	0.2200	18.54
NWC	5.101	0.0368	10.60
LWAC	16.843	0.0380	27.79

10.3.6 Scanning electron microscopy (SEM)

The Figure 10.4 shows the morphology of the expanded clay. It was verified that the external surface of this aggregate presents roughness texture than the internal surface of the sample. It can be seen that the internal surface presents larger amount of pores, with interconnectivity, responsible for its higher absorption.

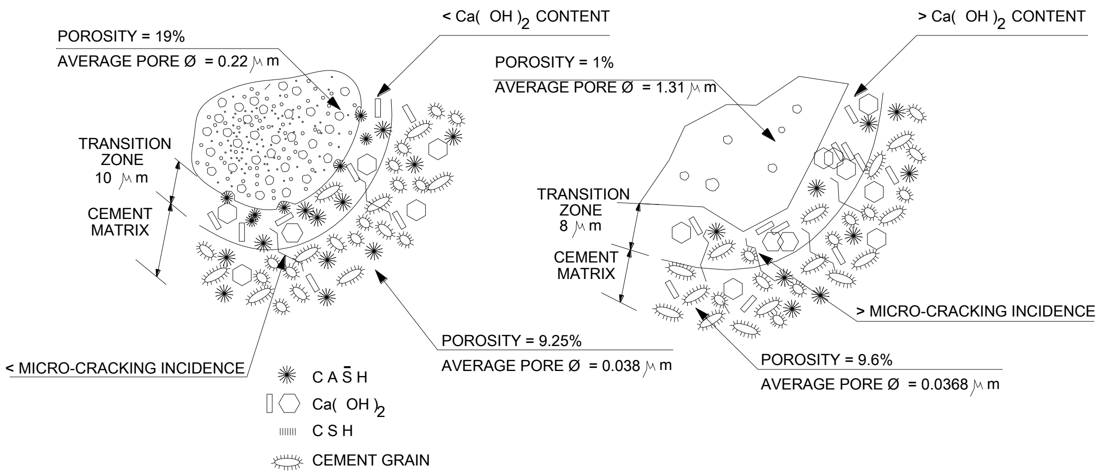


(a) external surface (300X) (b) internal surface (300X)

Figure 10. 4 – scanning electron microscopy images of expanded clay.

10.3.5 Transition zone models

The Figure 10.5 presents the transition zone between expanded clay and cement matrix in lightweight concrete and limestone and cement matrix in normal-weight concrete.



(a) expanded clay – cement matrix (b) limestone – cement matrix

Figure 10. 5 – Transition zone models.

The models indicate a transition zone more denser and homogeneous for LWAC in relation to NWC. That verification is due to factors evaluated in the study of those materials, as: the largest thermal stability of the lightweight aggregate and of the LWAC, the pozzolanic activity that occurs between the powder of expanded clay adhered to its own surface and the CH of the concrete, the best mechanical adherence between the lightweight aggregate and the cement matrix caused by the paste absorption (Chapter 4,5 and 8). Besides these factors it should be considered the internal cure, the modulus of elasticity and the shrinkage of LWAC. The internal cure promoted by the liberation of the absorbed water by the lightweight aggregate, forms new hydrated composites that will fill out empty spaces of the transition zone (Chapter 7). The smallest modulus of elasticity and the smallest shrinkage in LWAC promote a smaller internal stress in this concrete (Chapter 9), contributing to a smaller incidence of cracks and smaller connectivity of the pores in relation to NWC. The factors above, acting in an independent way, or associated, contribute to a transition zone with better characteristics in LWAC, and consequently for a larger durability of that concrete in relation to NWC.

10.4 CONCLUSION

Stereological Parameters can be used to obtain geometric, metric and morphologic information of the aggregates and of the cement matrix of concretes. The Quantikov program can substitute studies that need to be accomplished in the laboratory, using obtained images of the sections of the specimens of concrete, which would facilitate the obtaining of results as distribution of particles, maximum dimension characteristic and module of thinness. In that way there would be a reduction of costs with labor and with energy.

The program may help in the determination of the mortar content of structures of concretes already executed from the extraction of samples of the structure. This way, information of structures of the concrete can be obtained even when the proportion of its representatives is unknown.

The models of the transition zone between the coarse aggregate and the cement matrix of NWC and LWAC present the characteristics of those phases. These models can be used to explain the differences of behavior observed in that work, and by other authors, when we compared NWC to LWAC.

10.5 REFERENCES

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11 CONCLUSÕES

A massa unitária da argila expandida foi igual a 460 kg/m^3, enquanto que a brita calcária apresentou um valor igual a 1638 kg/m^3, evidenciando a grande diferença de densidade entre esses agregados. A dimensão máxima característica obtida para o agregado leve foi igual a 19 mm, e não foi possível classificar granulometricamente esse agregado, de acordo com as especificações da norma NBR 7211, pois as porcentagens retidas acumuladas por peneira não estão dentro dos limites granulométricos estabelecidos por esta norma.

A argila expandida apresentou alta porosidade (19%) em relação aos agregados convencionais (1%), devido à estrutura porosa dos seus grãos, o que corroborou para sua alta absorção de água. Esta elevada absorção, quando não prevista, descaracteriza o traço do concreto prejudicando suas propriedades mecânicas.

A argila expandida apresentou basicamente SiO_2, Fe_20_3, Al_2O_3, em sua composição química, e a presença de um halo de amorfismo na análise por difração de raios X, evidenciou a presença de fases amorfas, que foram formadas durante o processo de fabricação da argila expandida.

O concreto com agregado leve apresentou uma redução de 22% a 28% na resistência à compressão, em relação ao concreto de referência. Para uma resistência estimada de 40 MPa, o concreto de referência apresentou massa específica média igual a 2409 kg/m^3, enquanto que o valor médio obtido para o concreto leve foi de 1645 kg/m^3, resultando em uma redução em torno de 764 kg/m^3 de concreto.

Os concretos leves analisados podem ser classificados como estruturais segundo a norma ASTM C 330-77 (1991), pois apresentaram valores de massa específica entre 1.400 kg/m^3 e 1800 kg/m^3, e resistência à compressão aos 28 dias de idade superior a 17 MPa.

Os valores encontrados para o módulo de elasticidade estático do concreto leve estão na faixa entre 15 GPa e 17 GPa, situando-se no terço médio dos valores obtidos para o concreto de referência.

O concreto leve apresentou menor difusividade térmica e uma redução em torno de 55% na condução de calor em relação ao concreto de referência. Essa grande diferença pode ser explicada pela baixa condutividade térmica do ar presente nos poros do agregado leve.

O concreto leve apresentou maior estabilidade térmica que o concreto de referência, quando submetido a variações de temperatura de 25 a 950°C. Conclui-se, portanto, que o concreto leve apresenta maior resistência térmica em relação aos mesmos traços do concreto convencional.

Os valores obtidos para o coeficiente de expansão térmica do concreto leve, se aproximaram mais dos valores de expansão térmica das argamassas em relação aos coeficientes de expansão do concreto convencional. Portanto, no concreto leve, provavelmente, ocorrem menores tensões térmicas em seu interior, devido à menor diferença entre os coeficientes de expansão térmica da argamassa e da argila expandida, o que contribui para uma menor incidência de micro fissuras e para a uma maior durabilidade desse tipo de concreto.

Para uma resistência estimada de 40 MPa aos 28 dias de idade o concreto leve apresentou uma resistência à abrasão, ligeiramente maior, em relação ao concreto convencional. A melhor aderência observada entre os poros da argila expandida e a argamassa pode ter compensado a menor resistência à compressão da argila expandida, resultando em uma melhoria da resistência à abrasão do concreto leve.

Apesar da alta porosidade, o concreto leve apresentou menor absorção de água por capilaridade e um coeficiente de permeabilidade à água 10 vezes menor que o obtido para o concreto convencional. Isso pode ser explicado por um menor índice de fissuração devido ao seu melhor desempenho térmico e a prováveis melhorias ocorridas na zona de transição entre a argila expandida e a matriz de cimento. Esse comportamento indica, qualitativamente, maior resistência à ação de fluidos agressivos e, consequentemente, maior durabilidade do concreto leve em relação ao concreto convencional.

A água absorvida pela argila expandida com o tempo se torna disponível para realizar hidratações adicionais na zona de transição do concreto leve. Este fenômeno pode contribuir para a formação de uma zona de transição mais densa e com menor incidência de micro fissuras no concreto leve quando comparado ao concreto convencional.

O pó aderido na superfície da argila expandida apresentou propriedades pozolânicas. Esse fenômeno indica uma provável ocorrência de um maior índice de atividade pozolânica no concreto leve, corroborando para a formação de uma zona de transição mais densa e homogênea, e consequentemente, para uma maior durabilidade desse concreto em relação ao concreto convencional.

A relação entre as bandas de portlandita e etringita, obtida na análise de espectrometria no infravermelho, foi menor no concreto leve, indicando um menor teor de CH na zona de transição entre o agregado graúdo e a matriz de cimento nesse concreto em relação ao concreto convencional. Esse resultado confirma a hipótese de que ocorre um maior índice de atividade pozolânica na zona de transição do concreto leve em relação à que ocorre na zona de transição do concreto convencional.

Pode-se concluir, qualitativamente, que a interface agregado graúdo - matriz de cimento é menos evidenciada para os concretos leves, caracterizando a maior aderência entre este agregado a matriz de cimento. Para agregados porosos ou com uma superfície rugosa, a pasta de cimento ou produtos de sua hidratação podem penetrar nas cavidades ou poros da superfície desse agregado, aumentando a aderência através de uma interligação mecânica.

A análise química elementar, no geral, evidenciou uma redução dos teores de cálcio e um aumento dos teores de sílica na interface entre a argila expandida e a matriz de cimento em relação àquela formada entre a brita e a matriz de cimento. Acredita-se que isto pode reduzir a formação do composto hidróxido de cálcio e corroborar para a formação do silicato de cálcio hidratado, promovendo uma densificação da zona de transição.

A absorção de água pela argila expandida, pode dificultar a evaporação dessa água e contribuir para uma menor retração no concreto leve em relação ao concreto convencional, durante o processo de secagem, até que a água seja liberada em idades mais avançadas.

O menor módulo de elasticidade do concreto leve foi influenciado pelo menor módulo da argila expandida em relação ao da brita calcária. Esse resultado evidencia a maior capacidade do LWAC de absorver pequenas deformações como as causadas por esforços de retração, o que diminui as tensões internas e reduz a formação de microfissuras nesse concreto. Este comportamento contribui para uma maior durabilidade do concreto leve quando comparado ao concreto convencional.

12 CONTRIBUIÇÕES ESPECÍFICAS DESTE TRABALHO

- Realização de um estudo abrangente sobre diversas propriedades do concreto leve, comparando-as com as do concreto convencional.

- Identificação do principal fator responsável pela maior durabilidade do concreto leve em relação ao concreto convencional. Esse fator está associado à porosidade intrínseca do agregado leve, que foi responsável pelo melhor desempenho térmico desse concreto, e pelos fenômenos físicos e químicos ocorridos na zona de transição.

- Identificação do mecanismo responsável pela redução na retração autógena e na formação de micro fissuras no concreto leve. Esse mecanismo está relacionado ao fluxo de água causado pela sucção da argila expandida logo após a mistura do concreto leve, e não pela liberação da água pelo agregado leve conforme citado por outros autores. Esse fluxo equilibra as diferenças de concentração de água existentes entre os poros do agregado e a argamassa desse concreto, e preenche os vazios capilares da argamassa, principalmente na zona de transição, reduzindo a formação de meniscos no interior desses capilares e evitando o surgimento de tensões de tração.

- Demonstração de uma zona de transição mais densa e com menor presença de microfissuras no concreto leve, devido à atividade pozolânica do pó presente na superfície da argila expandida, ao menor teor de hidróxido de cálcio na matriz cimentícia, ao menor módulo de elasticidade do concreto leve, e aos fenômenos físicos e químicos provocados pela absorção do agregado leve.

- Apresentação de modelos da zona de transição entre o agregado graúdo e a matriz de cimento para o concreto leve e para o concreto convencional. Esses modelos podem ser utilizados para explicar as diferenças de comportamento entre o concreto convencional e o concreto leve. Utilização da estereologia, como uma nova alternativa, para a caracterização física de concretos.

- Demonstração da influência de parâmetros microestruturais do concreto leve em propriedades que estão diretamente relacionadas com a durabilidade, tais como permeabilidade, resistência térmica, retração, e resistência à abrasão.

13 SUGESTÕES PARA TRABALHOS FUTUROS

1. Continuar o estudo das relações entre microestrutura e propriedades do concreto, procurando estabelecer correlações matemáticas, com base em um planejamento estatístico de experimentos e/ou formulações.

2. Quantificar as fases presentes na zona de transição utilizando parâmetros estereológicos.

3. Estudar o comportamento do concreto leve simulando sua exposição ao gelo e degelo e em processos de carbonatação.

4. Verificar as propriedades do concreto leve utilizando outros tipos de cimento, acrescentando aditivos e adições.

5. Estudar a mecânica da fratura para concreto leve.